Searches for the Higgs Boson Before the Advent of the LHC

Roger Wolf

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INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (IEKP) – PHYSICS FACULTY

Recap from Last Time

Karlsruhe Institute of Technology

- Up to now...
  - Learned about the power of local gauge theories...

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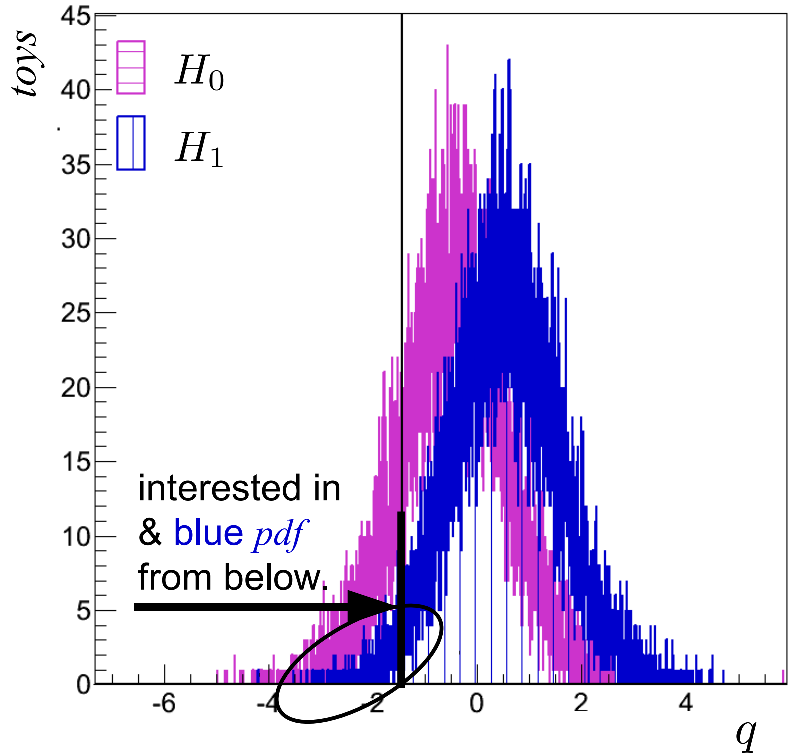
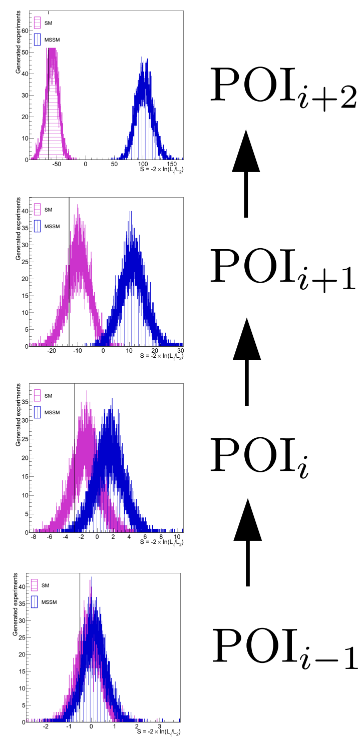
  - Learned about a way out → keep the symmetries in theory but not in praxis (spontaneous symmetry breaking).
  - Made a walk through the SM all inclusive.
  - Learned how to get from $\mathcal{L}$ to real measurements and how higher order in perturbation theory affect real measurements.
  - Reviewed what needs to be done to actually do these experimental measurements.
  - Reviewed the statistical methods/tools needed to search for the Higgs boson.

Recap from Last Time (Limits on POIs)

- Our *pdf*'s usually depend on another parameter, which is the actual *POI* (μ in SM, $\tan\beta$ in MSSM case).
- Traditionally we set 95% CL upper limits on this POI.





- *pdf*'s move apart from each other.
- The more separate the *pdf*'s are the more H_0 & H_1 are distinguishable.
- Find POI_i for which:

  $\mathcal{I}_{\mathrm{POI}} = \int_{-\infty}^{q_{\mathrm{obs}}} pdf = 0.05$

  for this POI_i in 95% of all toys $q \geq q_{\mathrm{obs}}$.

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95% CL Upper Limit:

- POI_i is the value at which in case that H_1 is the true hypothesis the chance that $q \geq q_{\mathrm{obs}}$ is 95%.
- Still there is a chance of 5% that $q < q_{\mathrm{obs}}$.

- Assume our POI is μ: does the 90% CL upper limit on μ correspond to a higher or a lower value $\mu_{90\%}$? → It's lower!

$\mu_{99\%}$ → 1%

$\mu_{95\%}$

$\mu_{90\%}$ → 10%

} probability of q to be "more background like" than q_{obs}.

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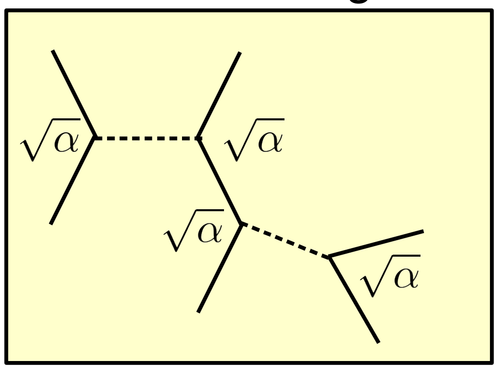
Recap from Last Time (Effects of loop corrections)

- We have only discussed contribution to $\mathcal{S}_{fi}$, which are of order α^1 in QED. (e.g. LO $ee \to ee$ scattering) .

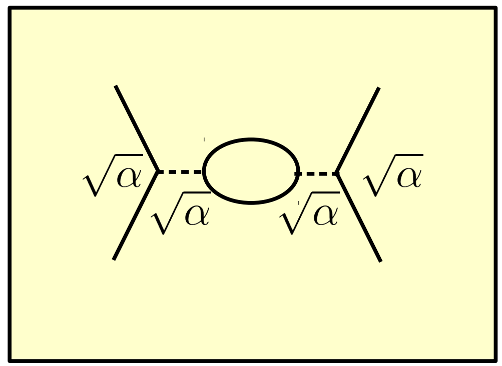
- Diagrams which contribute to order α^2 would look like this:

Additional legs:



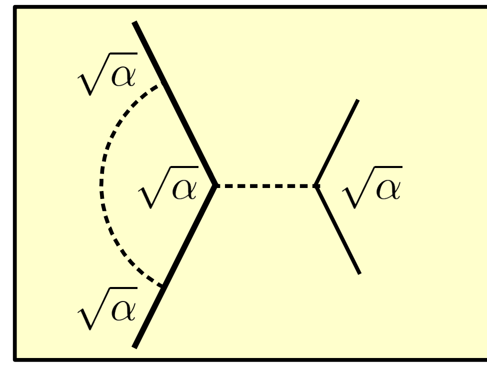
- LO term for a $2 \to 4$ process.
- NLO contrib. for the $2 \to 2$ process.
- Open phase spaces.

Loops:



(loops in propagators or legs)

- Modify (effective) masses of particles ("running masses").



(loops in vertexes)

- Modify (effective) couplings of particles ("running couplings").

Quiz of the Day

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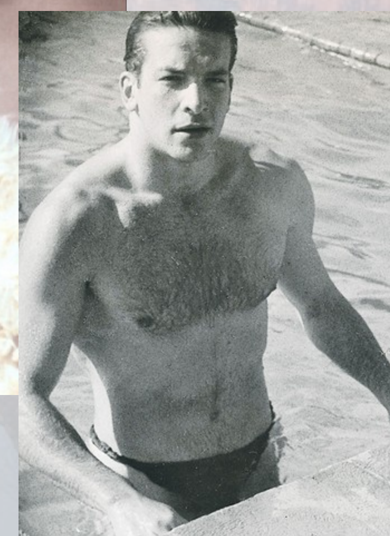


Bud Spencer = Carlo Pedersoli

Schedule for Today

Distribution of Seminar Topics at the end of this lecture!

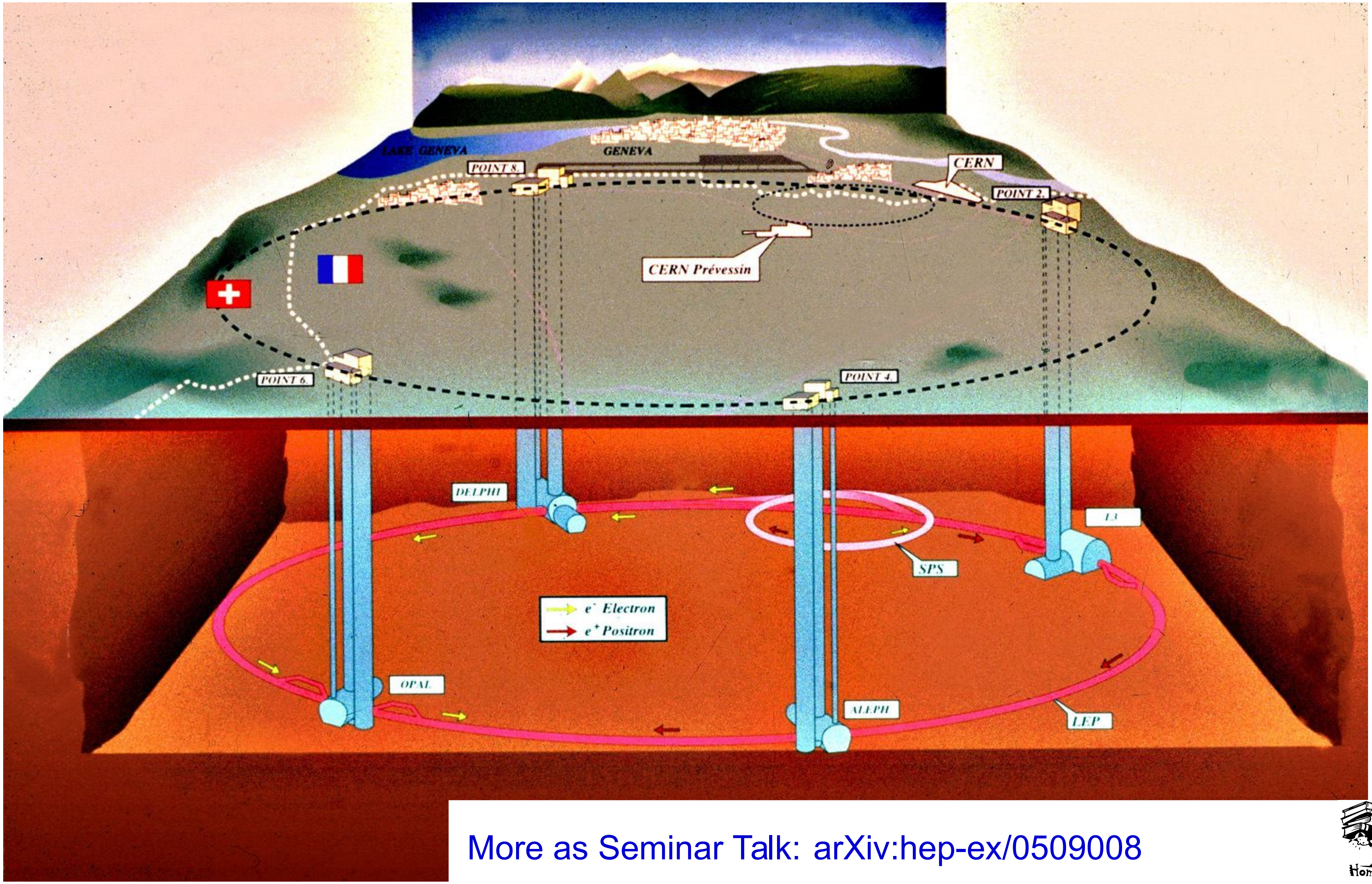
2

Direct Higgs Boson searches at LEP and Tevatron.

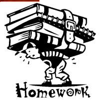
1

Indirect constraints on m_H from high precision measurements.

High Precision Measurements @ LEP & SLAC



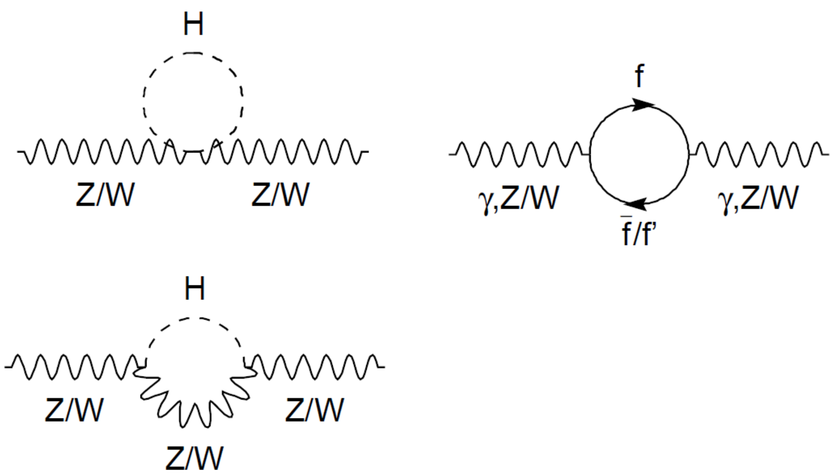
More as Seminar Talk: arXiv:hep-ex/0509008



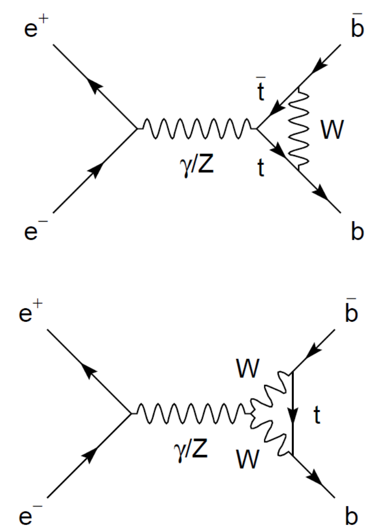
Higher Orders on Precision Observables

- Particles, which cannot be directly observed at lower energy scales, still have influence on observables, due to higher order corrections in loops.

The Higgs/*top* in propagator loops:



The *top* in vertex loops:



- Introduce direct dependencies of effective (measurable) vector boson masses and couplings on m_H & m_t.

Higher Order Corrections to m_W

- Higher order corrections to m_W:

$$m_W^2 = \frac{m_Z^2}{2}\left(1+\sqrt{1-4\frac{\alpha\pi}{\sqrt{2}G_F m_Z^2}\cdot\frac{1}{1-\Delta r}}\right) \qquad \Delta r = \Delta\alpha + \Delta r_W$$

$$\Delta\alpha = \Delta\alpha_{\mathrm{lep}} + \Delta\alpha_{\mathrm{top}} + \Delta\alpha_{\mathrm{had}}^{(5)}$$

$$\Delta r_W(m_t, m_H) \simeq \frac{\alpha}{\pi\sin^2\theta_W}\left(-\frac{3}{16}\frac{\cos^2\theta_W}{\sin^2\theta_W}\frac{m_t^2}{m_W^2} + \frac{11}{24}\log\left({}^{m_H}/{}_{m_Z}\right)\right)$$

$$\propto m_t^2$$

$$\propto \log(m_H)$$

- Effects set in at $\mathcal{O}(\alpha^2) \approx \mathcal{O}(10^{-4}) \rightarrow$ high precision needed on observables and theoretical prediction!

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$\propto m_t^2$

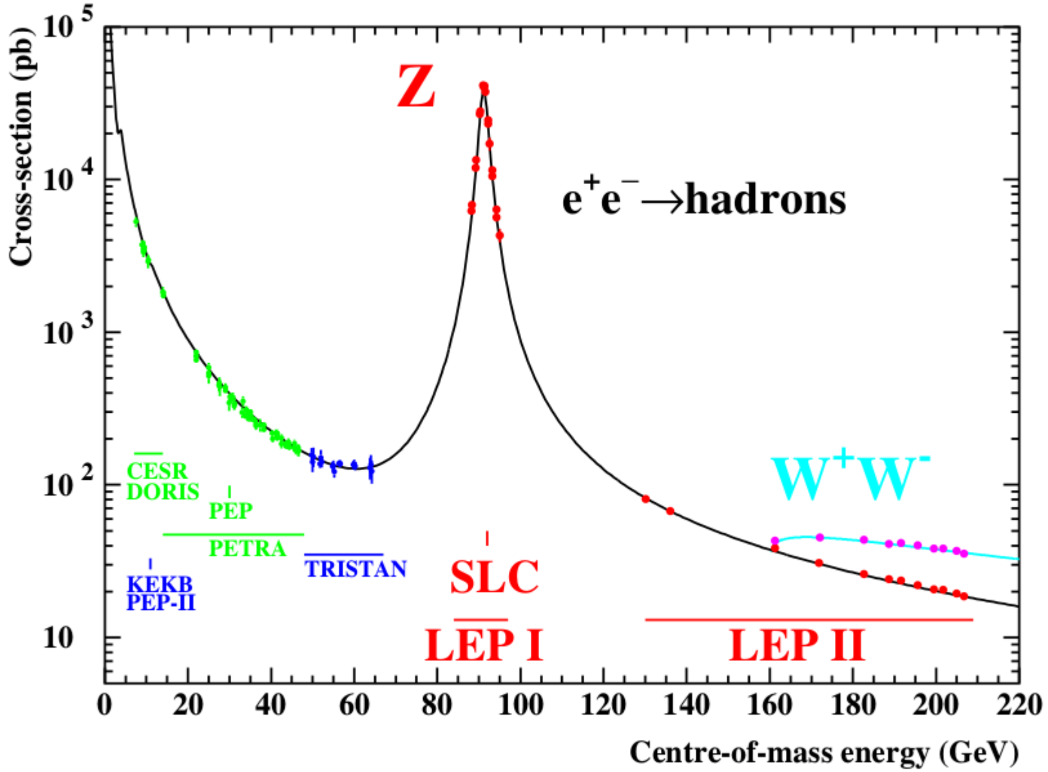
$\propto \log\left(m_H\right)$

Largest theoretical uncertainty.

- Effects set in at $\mathcal{O}(\alpha^2) \approx \mathcal{O}(10^{-4}) \rightarrow$ high precision needed on observables and theoretical prediction!

High Precision Observables @ LEP

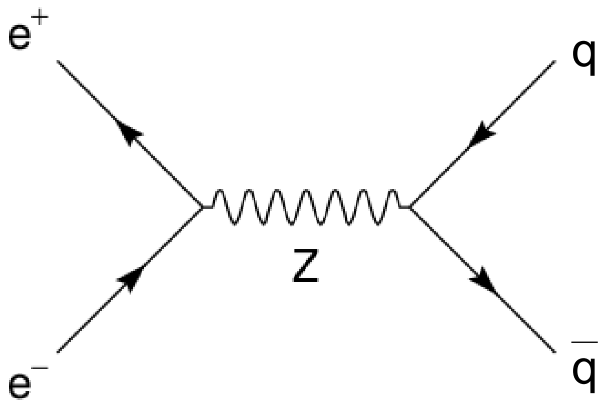
- High precision measurements made at $\sqrt{s} = m_Z$ during LEP-I run period:

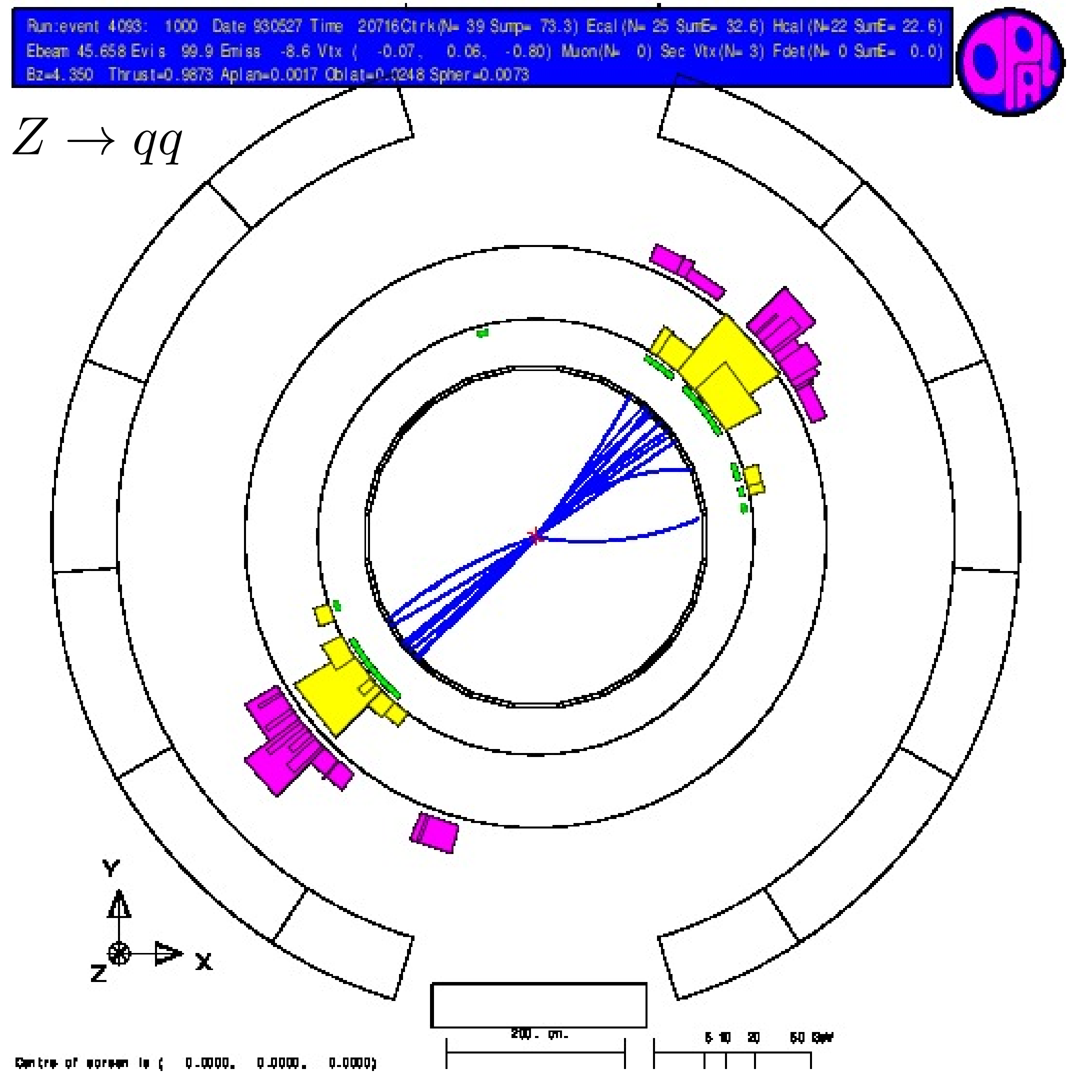


Year	Centre-of-mass energy range [GeV]	Integrated luminosity [pb^{-1}]
1989	88.2 – 94.2	1.7
1990	88.2 – 94.2	8.6
1991	88.5 – 93.7	18.9
1992	91.3	28.6
1993	89.4, 91.2, 93.0	40.0
1994	91.2	64.5
1995	89.4, 91.3, 93.0	39.8
		202.1

- $15 \cdot 10^6 \ Z \to qq$ events
- $1.7 \cdot 10^6 \ Z \to \ell\ell$ events

Typical $Z \to qq$ Event @ LEP





Z-pole Electroweak Precision Observables

Pseudo-Observable	Measured Value		
$\Delta\alpha^{(5)}_{\text{had}}(m_Z)$	0.02758	$\pm$	0.00034
m_Z [GeV]	91.1875	$\pm$	0.0021
Γ_Z [GeV]	2.4952	$\pm$	0.0023
σ^0_{had} [nb]	41.540	$\pm$	0.037
R^0_l	20.767	$\pm$	0.025
R^0_b	0.21629	$\pm$	0.00066
R^0_c	0.1721	$\pm$	0.0030
$A^{0,l}_{FB}$	0.0171	$\pm$	0.0010
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$A^{0,c}_{FB}$	0.0707	$\pm$	0.0035
$\sin^2\theta^{\text{lep}}_{\text{eff}}$	0.2324	$\pm$	0.0012
$\mathcal{A}_l(\mathcal{P}_\tau)$	0.1465	$\pm$	0.0033
$\mathcal{A}_b$	0.923	$\pm$	0.020
$\mathcal{A}_c$	0.670	$\pm$	0.027
$\mathcal{A}_l(\text{SLD})$	0.1513	$\pm$	0.0021

(as of arXiv:hep-ex/0509008)

- 15 observables.
- Precision between $\mathcal{O}(10^{-5})$ for m_Z & $\mathcal{O}(10^{-2})$ for $\mathcal{A}_l(\text{SLD})$ (incl. theoretical uncertainties).
- Exploit dependencies $\propto m_t^2$ and $\propto \log(m_H)$ of higher orders via relations in m_W and $\sin\theta_{\text{eff}}$.

NB: Using similar relations with the same dependencies as shown on slide 15f for m_W .

Shift $\Delta\alpha^5_{\text{had}}(m_Z)$

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- $\Delta\alpha^5_{\text{had}}(m_Z)$ as obtained from independent measurements at lower energies.

Z-pole Observables

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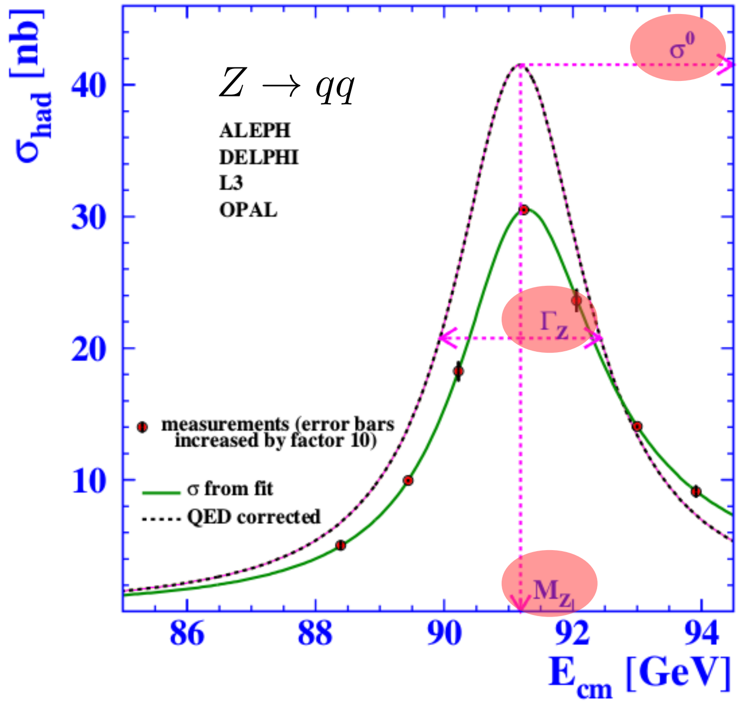

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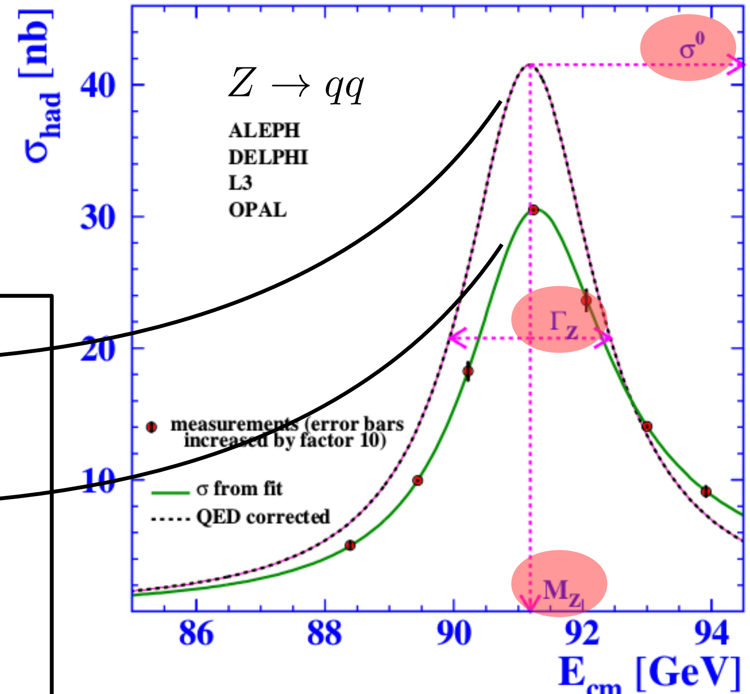
After correction for HO effects.

Actual measurement.

- ISR up to $\mathcal{O}(\alpha^3)$.
- FSR up to $\mathcal{O}(\alpha_s^3)$ and $\mathcal{O}(\alpha \cdot \alpha_s)$.
- ISR FSR interference effects up to $\mathcal{O}(\alpha)$.
- Since corrections are sizable these variables are referred to as "pseudo-observables".



Partial Decay Widths

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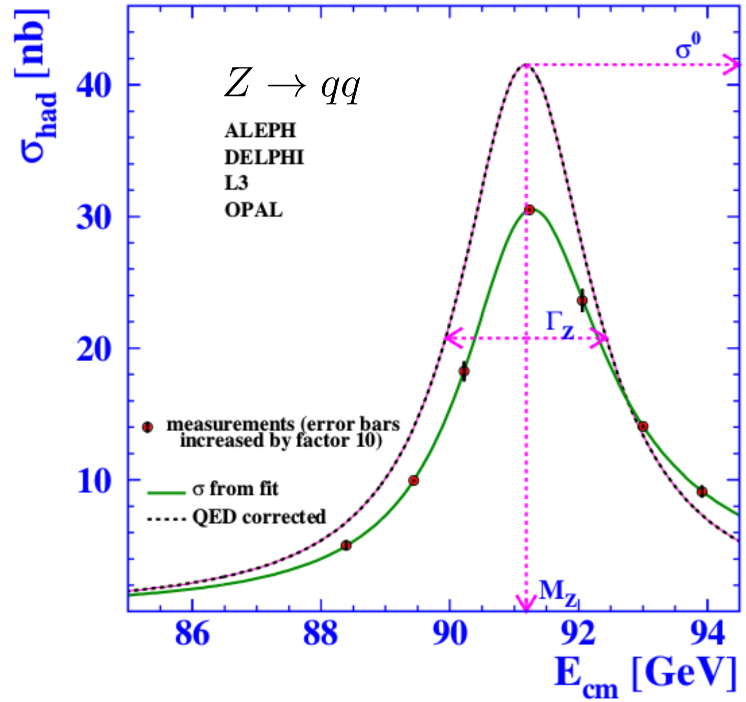

Ratios of partial decay widths:

$$R^0_\ell = \frac{\Gamma^0_{\mathrm{had}}}{\Gamma_{\ell\ell}} \qquad R^0_c = \frac{\Gamma_{cc}}{\Gamma^0_{\mathrm{had}}} \qquad R^0_b = \frac{\Gamma_{bb}}{\Gamma^0_{\mathrm{had}}}$$

$$\Gamma^0_{\mathrm{had}} = \frac{\sigma^0_{\mathrm{had}} m_Z^2}{12\pi} \cdot \frac{\Gamma_Z^2}{\Gamma_{ee}}$$

Asymmetries (→ sensitive to $\sin\theta_{\text{eff}}$)

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(as of arXiv:hep-ex/0509008)

- Z boson has different coupling to left- and right-handed fermions.
- Leads to:
  - net polarization in final states.
  - different rates on polarized beams.

$$\mathcal{A}_f = \left.\frac{g_L^2 - g_R^2}{g_L^2 + g_R^2}\right|_f = \left.\frac{2 g_V g_A}{g_V^2 + g_A^2}\right|_f$$

$$\left.\frac{g_V}{g_A}\right|_f = 1 - 4|Q_f|\sin^2\theta_{\text{eff}}$$

$$A^{0,f}_{FB} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

$$\langle\mathcal{P}^0_\tau\rangle = -\mathcal{A}_\tau$$

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Karlsruhe Institute of Technology

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Forward-Backwad Asymmetry

(as of arXiv:hep-ex/0509008)

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Asymmetries (→ sensitive to $\sin\theta_{\text{eff}}$)

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Left-Right Asymmetry

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Asymmetries (forward backward, exclusive)

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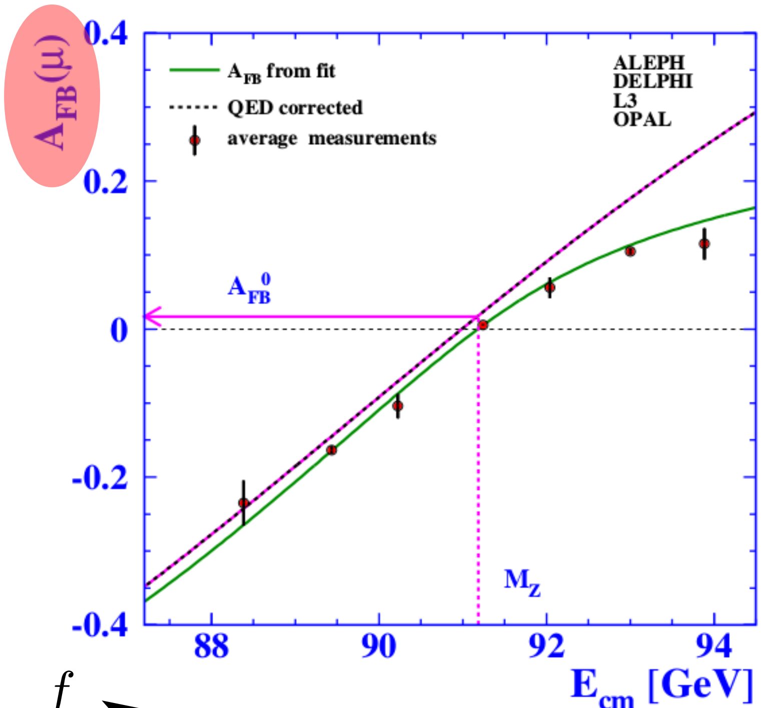
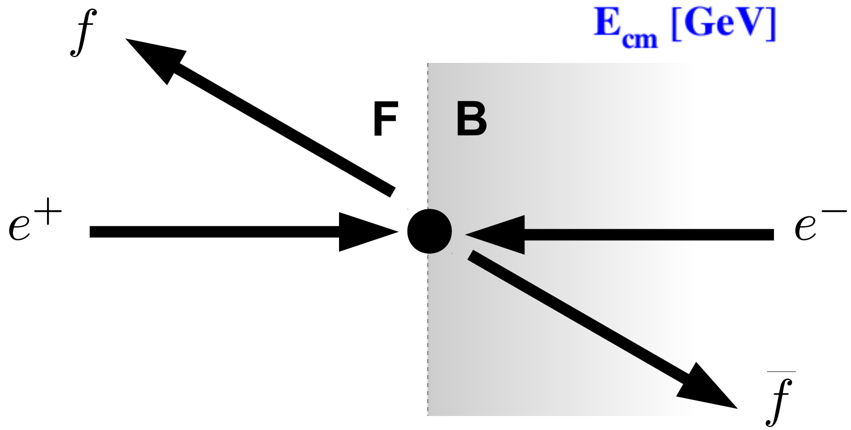




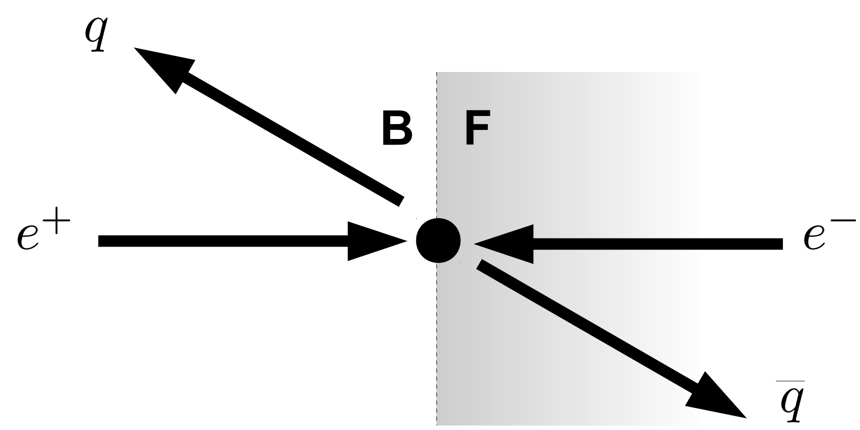
Asymmetries (forward backward, inclusive)

Pseudo-Observable	Measured Value		
$\Delta\alpha^{(5)}_{\text{had}}(m_Z)$	0.02758	$\pm$	0.00034
m_Z [GeV]	91.1875	$\pm$	0.0021
Γ_Z [GeV]	2.4952	$\pm$	0.0023
σ^0_{had} [nb]	41.540	$\pm$	0.037
R^0_l	20.767	$\pm$	0.025
R^0_b	0.21629	$\pm$	0.00066
R^0_c	0.1721	$\pm$	0.0030
$A^{0,l}_{FB}$	0.0171	$\pm$	0.0010
$A^{0,b}_{FB}$	0.0992	$\pm$	0.0016
$A^{0,c}_{FB}$	0.0707	$\pm$	0.0035
$\sin^2\theta^{\text{lep}}_{\text{eff}}$	0.2324	$\pm$	0.0012
$\mathcal{A}_l(\mathcal{P}_\tau)$	0.1465	$\pm$	0.0033
$\mathcal{A}_b$	0.923	$\pm$	0.020
$\mathcal{A}_c$	0.670	$\pm$	0.027
$\mathcal{A}_l$(SLD)	0.1513	$\pm$	0.0021

(as of arXiv:hep-ex/0509008)

- Determined from inclusive hadronic forward-backward charge asymmetry measurements at LEP.
- Usually directly expressed in terms of $\sin^2\theta^{\text{lep}}_{\text{eff}}$.

e.g. determined by jet charge



Asymmetries (left-right couplings from τ polarization)

Pseudo-Observable	Measured Value		
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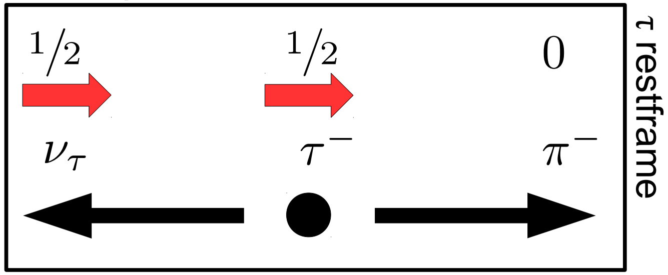
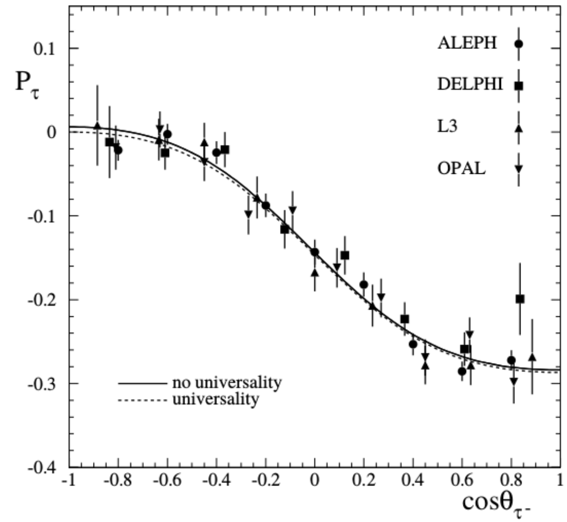
(as of arXiv:hep-ex/0509008)

- τ is the only fermion at LEP where polarization information can be derived from.

Example: $\tau^- \to \pi^- \nu_\tau$





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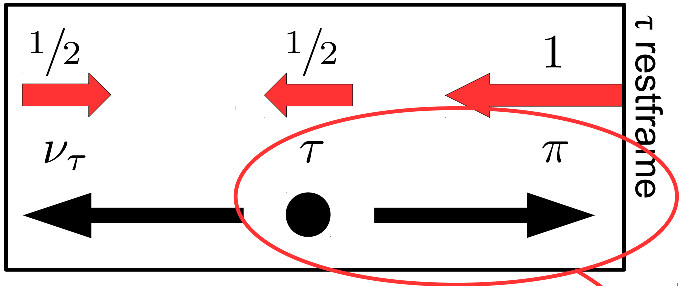

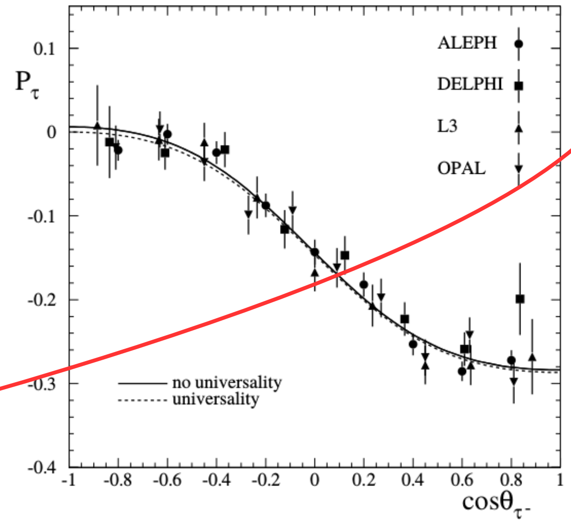

π moves in opposite direction of τ spin!

Asymmetries (left-right couplings @ SLD/SLAC)

Pseudo-Observable	Measured Value		
$\Delta\alpha^{(5)}_{\rm had}(m_Z)$	0.02758	$\pm$	0.00034
m_Z [GeV]	91.1875	$\pm$	0.0021
Γ_Z [GeV]	2.4952	$\pm$	0.0023
$\sigma^0_{\rm had}$ [nb]	41.540	$\pm$	0.037
R^0_l	20.767	$\pm$	0.025
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$\mathcal{A}_l(\mathcal{P}_\tau)$	0.1465	$\pm$	0.0033
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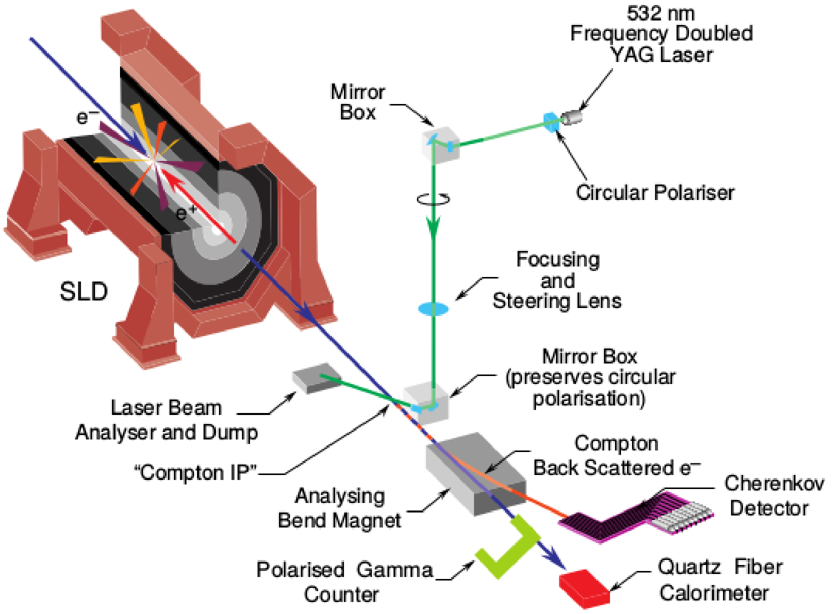
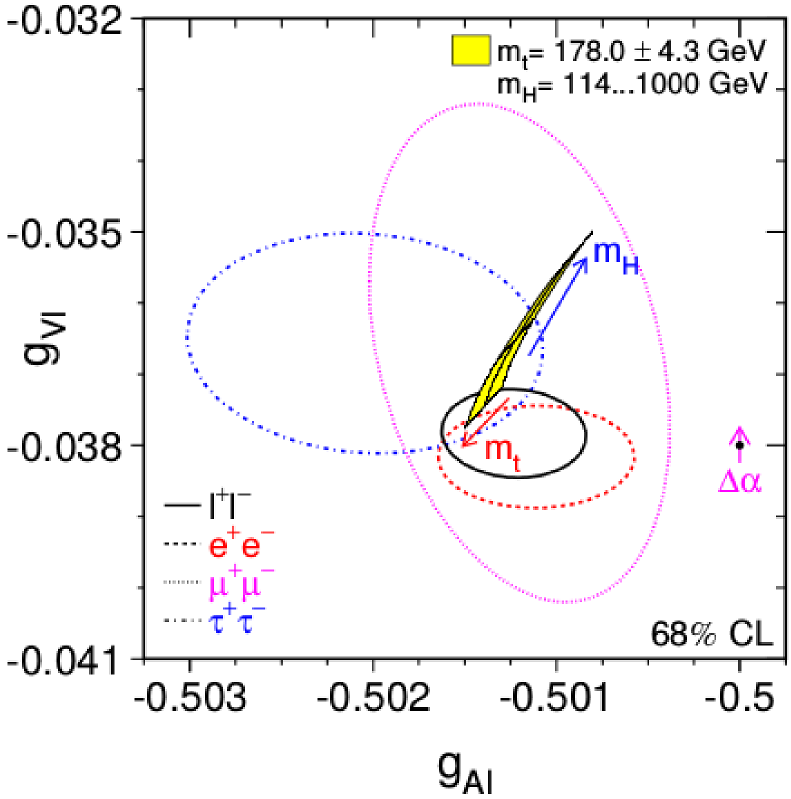
(as of arXiv:hep-ex/0509008)

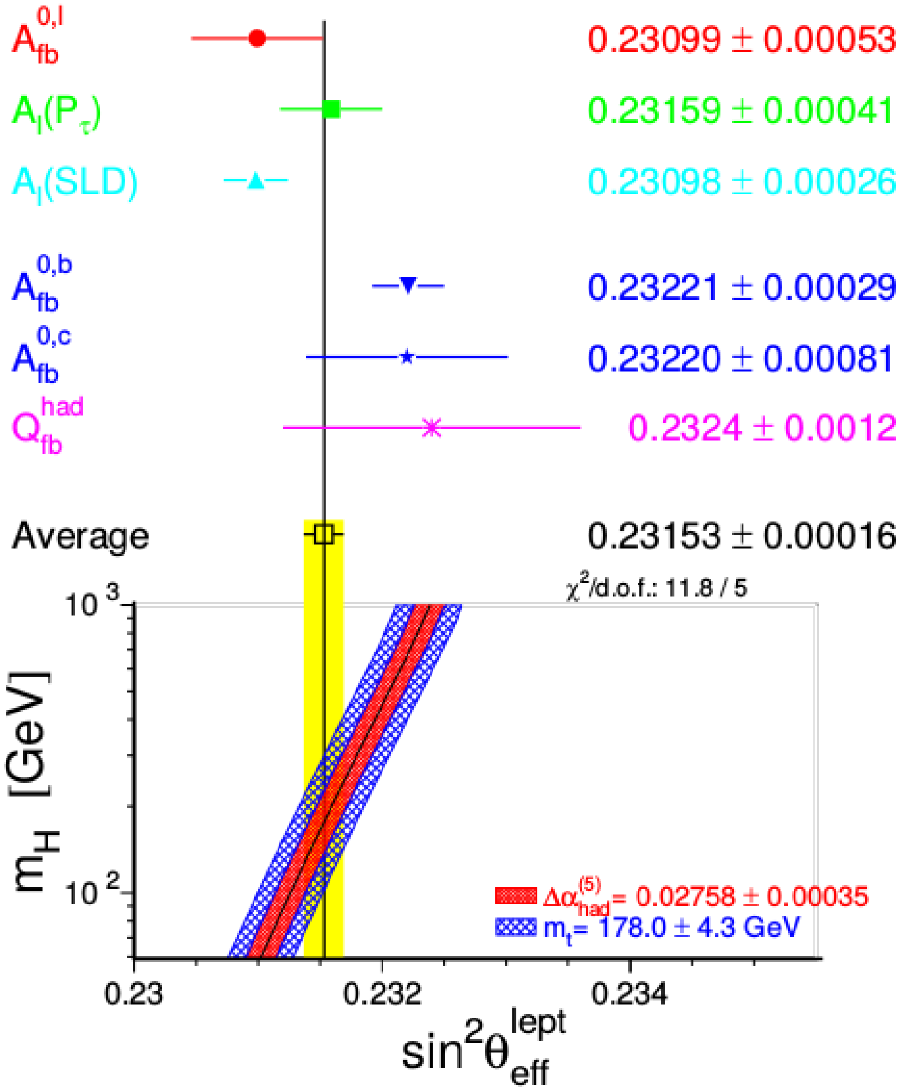
- Measured with polarized e^+ beam with the SLD experiment at SLAC.



Asymmetries (sensitivity to m_t and m_H)

- Lepton universality!
- Light Higgs boson preferred.

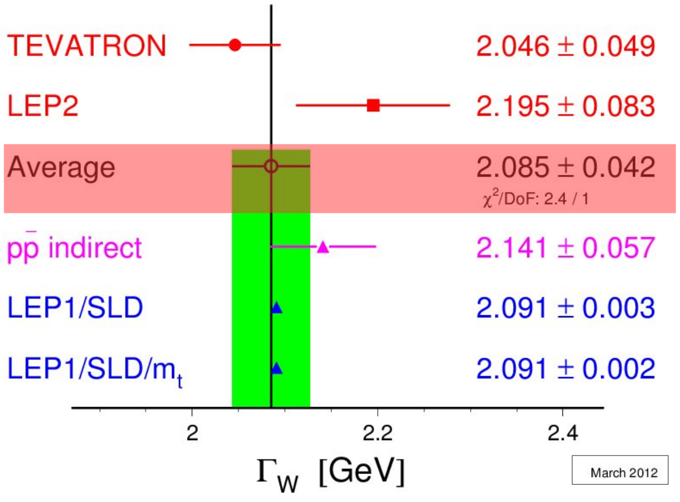


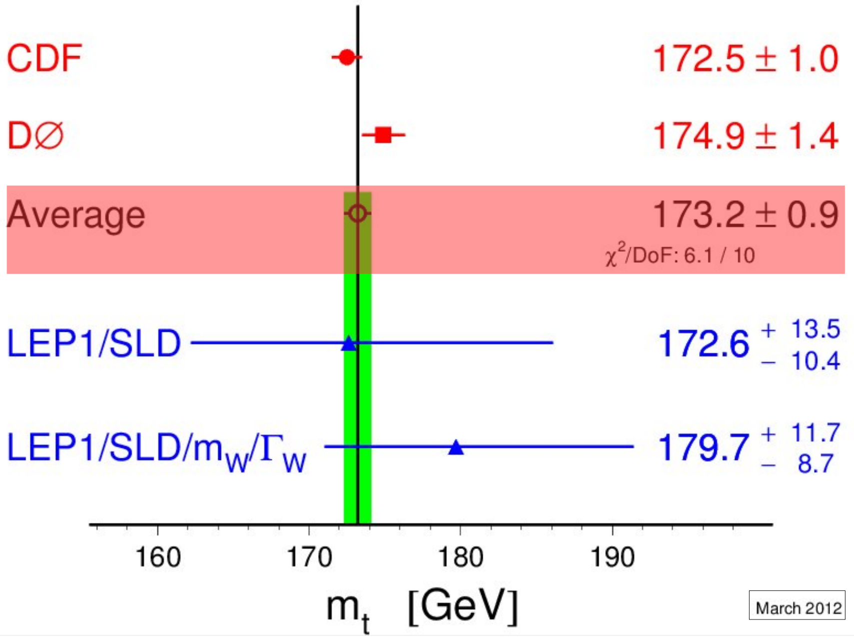


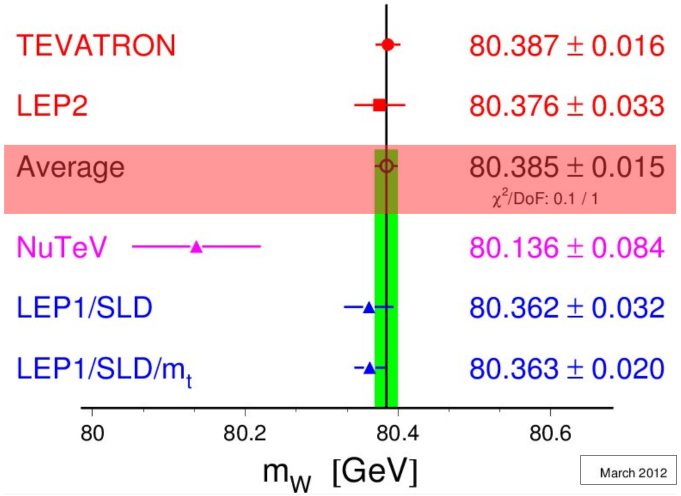
Additional measurements for maximal sensitivity

Pseudo-Observable	Measured Value
m_W [GeV]	80.385 ± 0.015
Γ_W [GeV]	2.085 ± 0.042
m_t [GeV]	173.2 ± 0.9

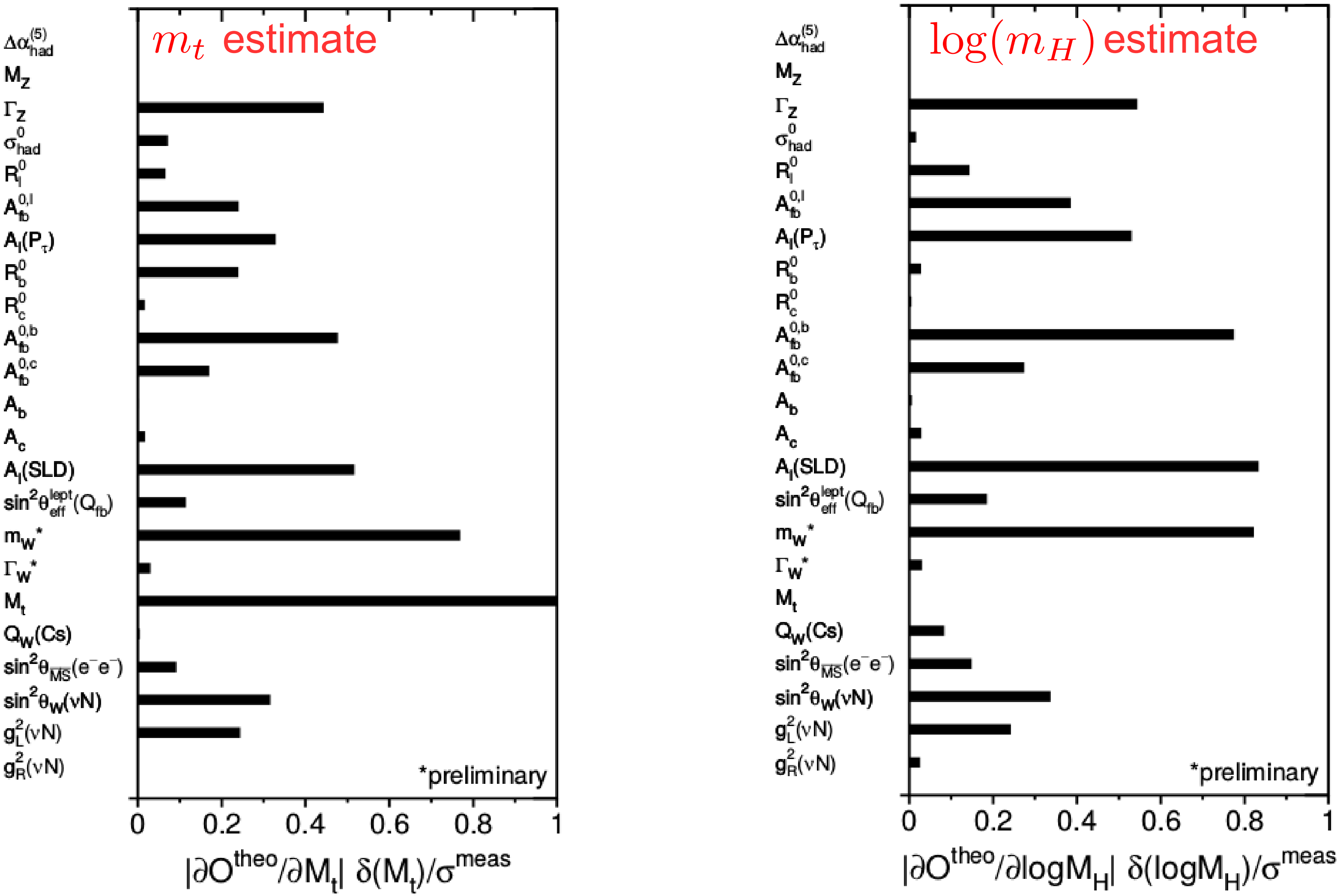
(as of March 2012)







Sensitivity (sensitivity to m_t and m_H)



Parameter Estimate

- Five parameter χ^2 fit:

Parameter	Best Fit Value	$\Delta\alpha^{(5)}_{\text{had}}(m_Z)$	$\alpha_s(m_Z)$	m_Z	m_t	$\log(m_H/\text{GeV})$
$\Delta\alpha^{(5)}_{\text{had}}(m_Z)$	0.02759 ± 0.00035	1.0				
$\alpha_s(m_Z)$	0.1190 ± 0.0027	−0.04	1.0			
m_Z	91.1874 ± 0.0021	−0.01	−0.03	1.0		
m_t	173 ± 11.5	−0.03	0.19	−0.07	1.0	
$\log(m_H/\text{GeV})$	2.05 ± 0.385	−0.29	0.25	−0.02	0.89	1.0

Fit of Z-pole observables only: (1)

$\chi^2/ndof = {}^{16}/_{10}$

$\mathcal{P}(\chi^2) = 9.9\%$

(2005)

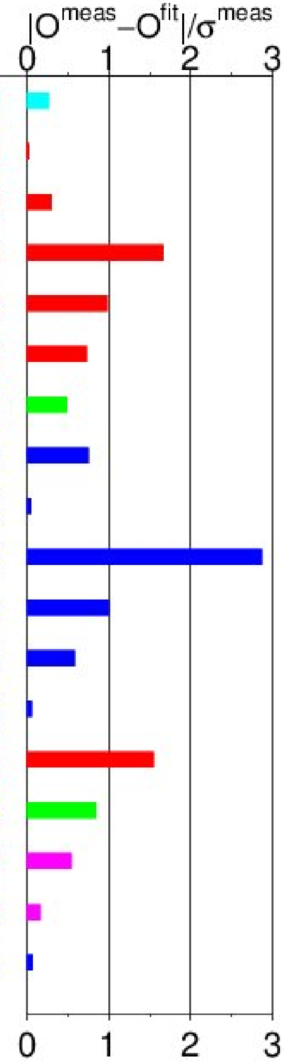
Fit of Z-pole observables + m_W, Γ_W, m_t: (2)

$\chi^2/ndof = {}^{16.9}/_{13}$

$\mathcal{P}(\chi^2) = 20.2\%$

(2012)

	Measurement	Fit
$\Delta\alpha^{(5)}_{\text{had}}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{\text{lept}}_{\text{eff}}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26

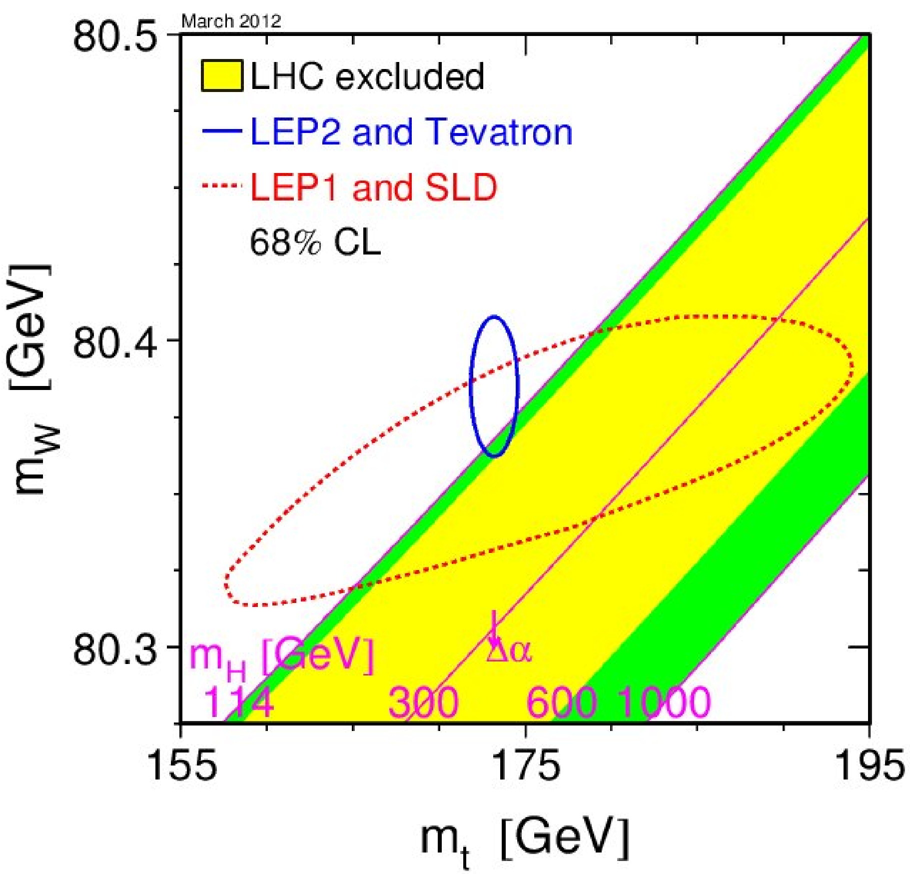


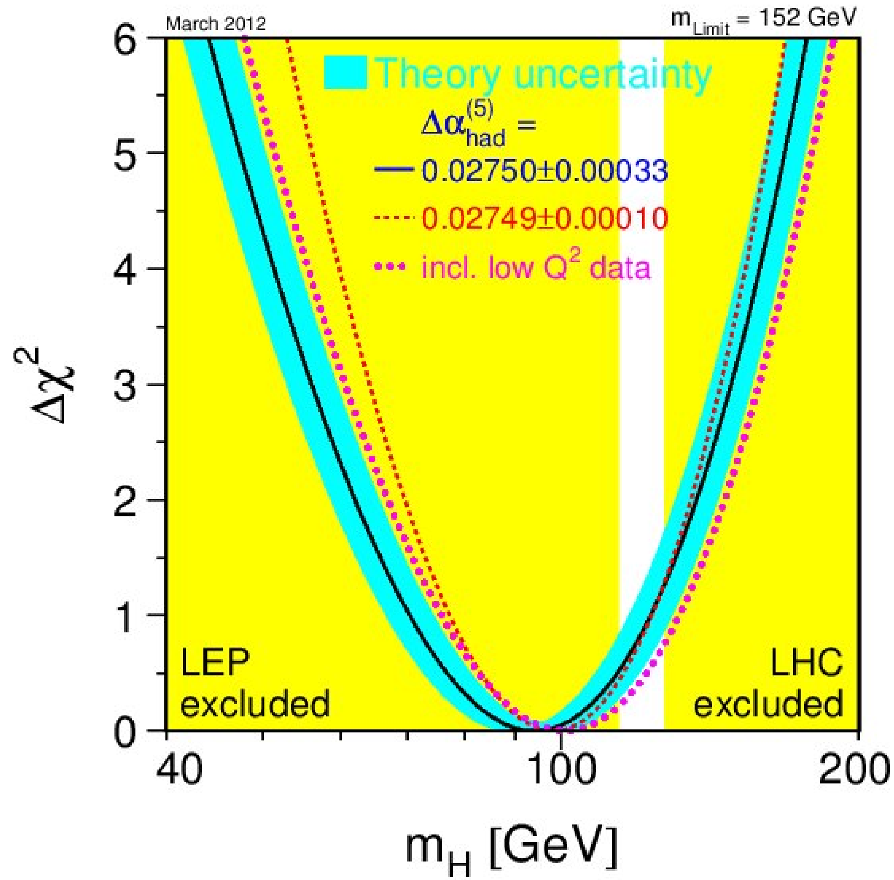
March 2012

(1) (as of arXiv:hep-ex/0509008)

(2) http://lepewwg.web.cern.ch/LEPEWWG/winter12_results

Main Result





Z-pole + m_W + Γ_W:

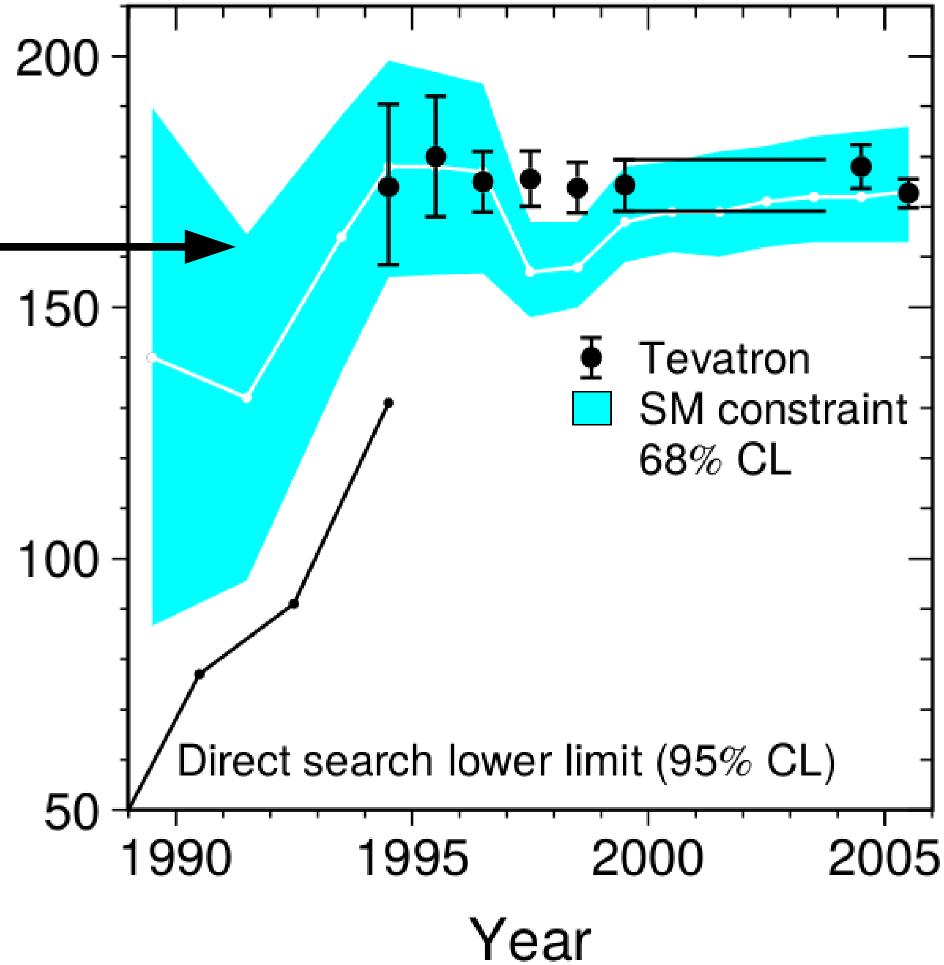
$m_t = 178.1 \pm^{10.9}_{7.8}$ GeV

Z-pole + m_W + Γ_W + m_t:

$m_H = 98 \pm^{25}_{21}$ GeV

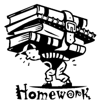
Pre-Discovery Constraints on m_t & m_H

- Consistency checks of the SM turned out as great success:
- Constraints on m_t spot on with direct measurements before discovery!
- Constraints on m_H in good agreement with direct measurements before discovery!



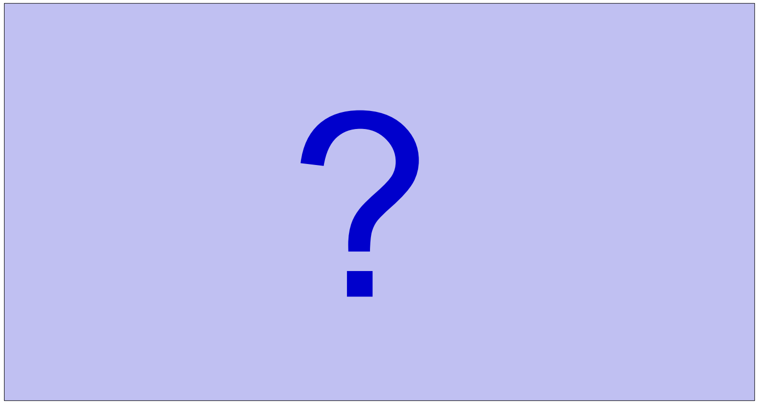
Direct Searches

More as Seminar Talk: arxiv:hep-ex/0306033



Direct Searches @ LEP

- Main production mode in e^+e^-:



- Higgs boson couples to mass.
- Strongest coupling to heaviest objects.

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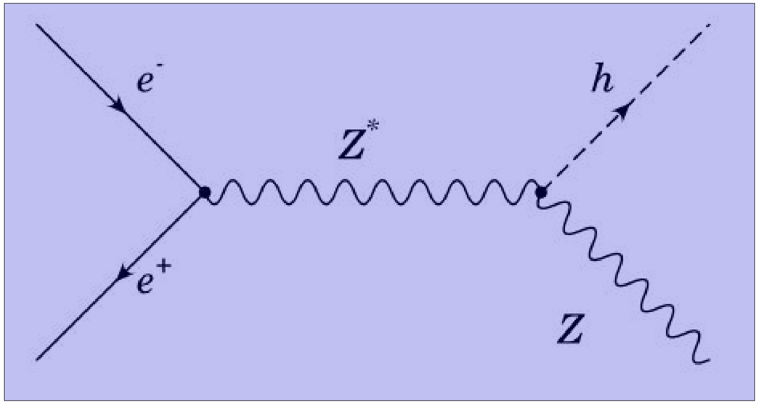

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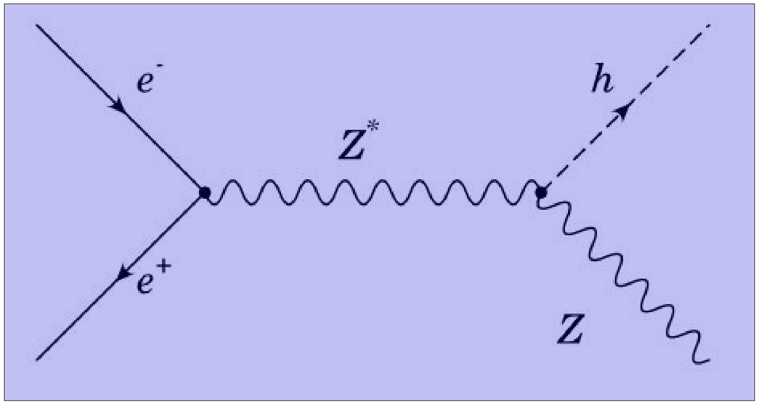
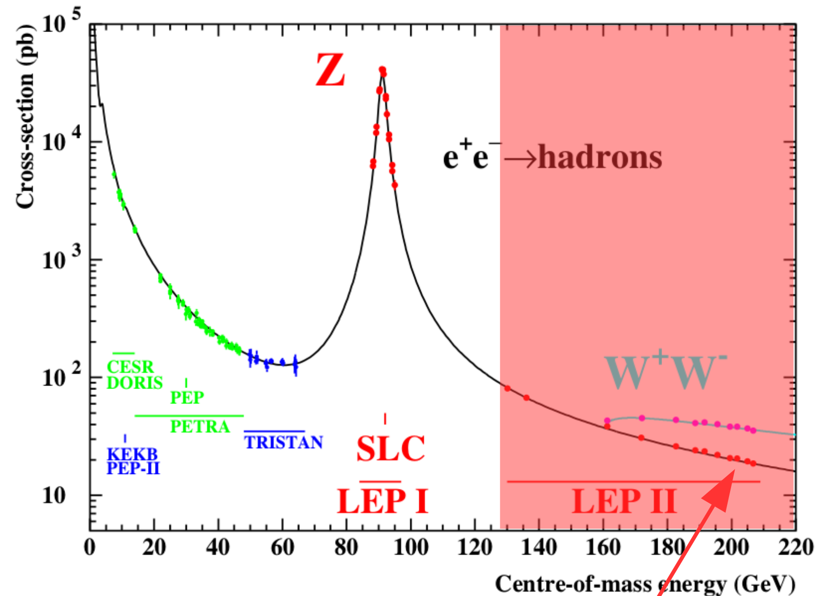


Integrated luminosities in pb^{-1}					
	ALEPH	DELPHI	L3	OPAL	LEP
$\sqrt{s} \geq 189$ GeV	629	608	627	596	2461
$\sqrt{s} \geq 206$ GeV	130	138	139	129	536



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Year	1996		1997	1998	1999				2000	
E_{CM} nominal [GeV]	161	172	183	189	192	196	200	202	205	207

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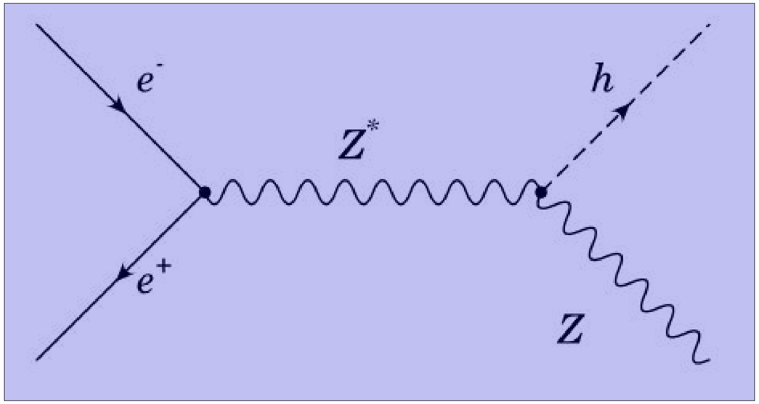

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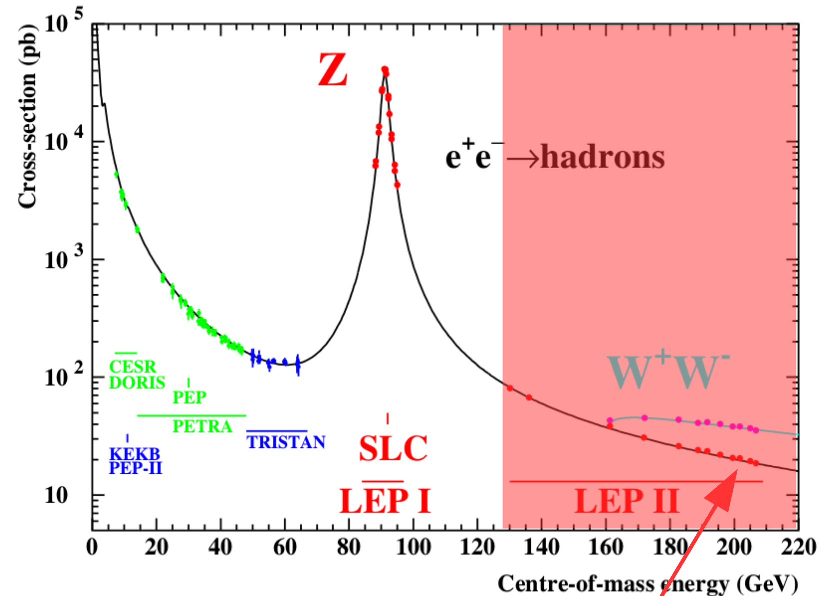

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What was the maximal reach on m_H at LEP?

Direct Searches @ LEP

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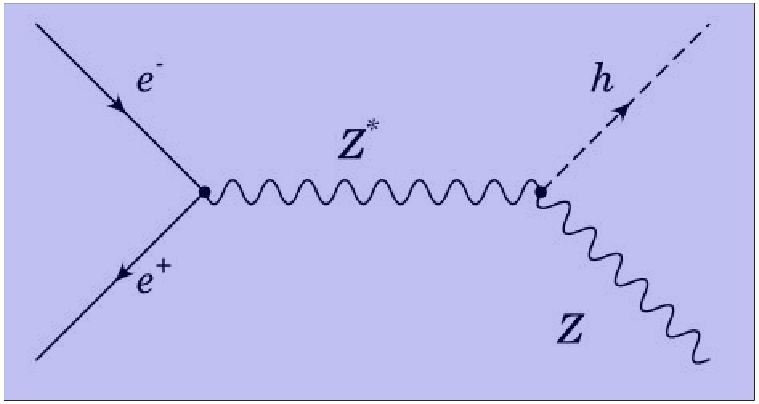

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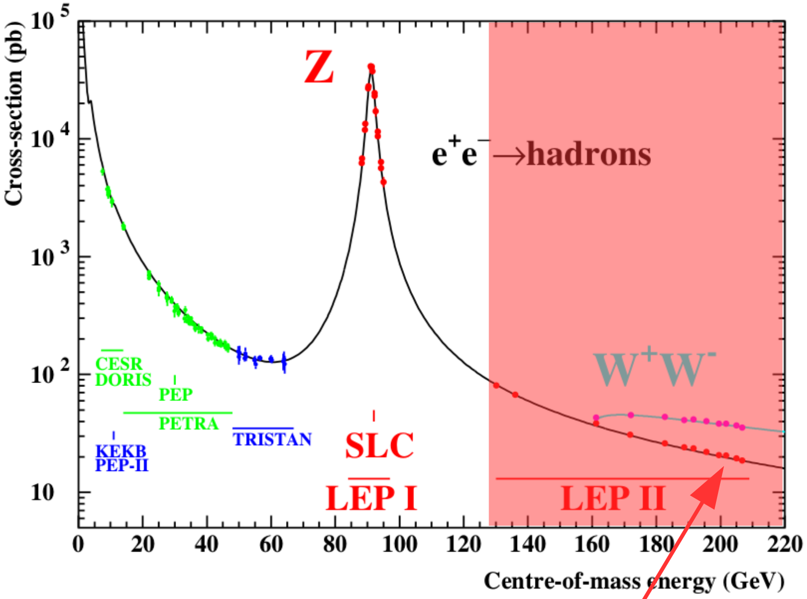

Year	1996		1997	1998	1999				2000	
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What was the maximal reach on m_H at LEP? → $m_H \approx 117$ GeV

Test Statistic (LEP, remember last lecture)

$$\mathcal{L}_{s+b} = \prod_{k=1}^{N} \left(\frac{(s_k+b_k)^{n_k}}{n_k!} e^{-(s_k+b_k)} \cdot \prod_{j=1}^{n_k} \frac{s_k S_k + b_k B_k}{s_k + b_k} \right)$$

$$\mathcal{L}_{b} = \prod_{k=1}^{N} \left(\frac{b_k^{n_k}}{n_k!} e^{-b_k} \cdot \prod_{j=1}^{n_k} \frac{b_k B_k}{b_k} \right)$$

$$Q = \frac{\mathcal{L}_{s+b}}{\mathcal{L}_b} = \prod_{k=1}^{N} \left(e^{-s_k} \cdot \prod_{j=1}^{n_k} \frac{s_k S_k + b_k B_k}{b_k B_k} \right)$$

$$q = -2 \ln Q = 2 \sum_{k=1}^{N} \left(s_k - \sum_{j=1}^{n_k} \ln \left(1 + \frac{s_k S_k}{b_k B_k} \right) \right)$$

What values of Q and q correspond to more signal/background like?

Test Statistic (LEP, remember last lecture)

$$\mathcal{L}_{s+b} = \prod_{k=1}^{N} \left(\frac{(s_k+b_k)^{n_k}}{n_k!} e^{-(s_k+b_k)} \cdot \prod_{j=1}^{n_k} \frac{s_k S_k + b_k B_k}{s_k + b_k} \right)$$

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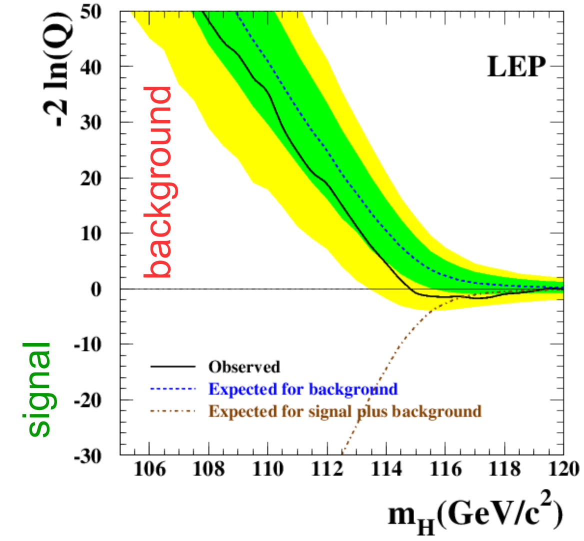

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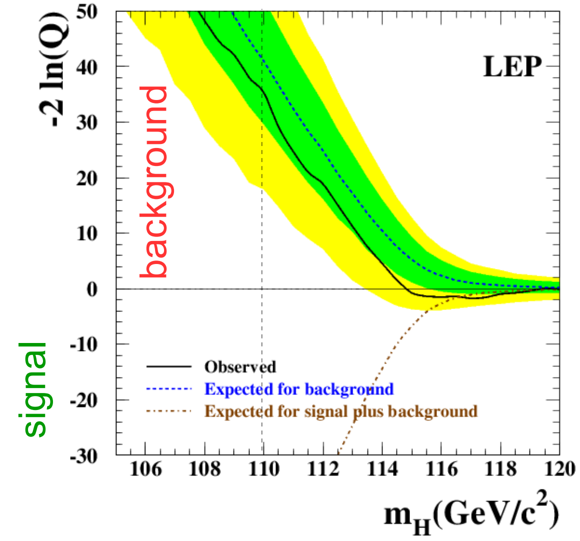

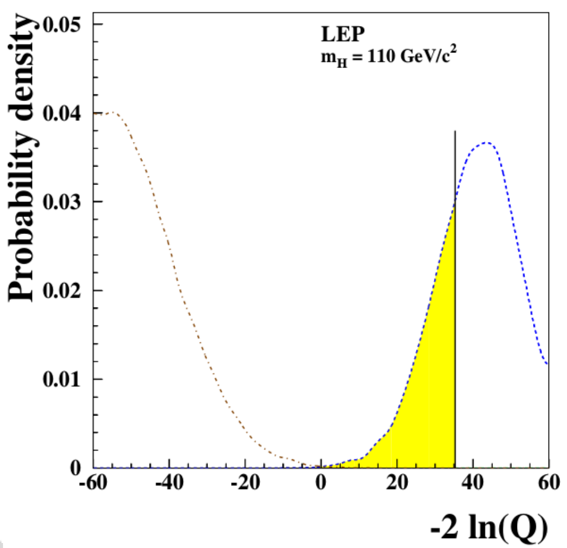

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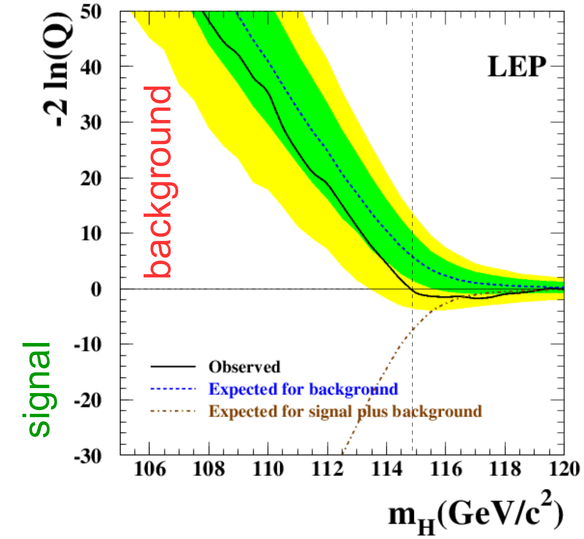
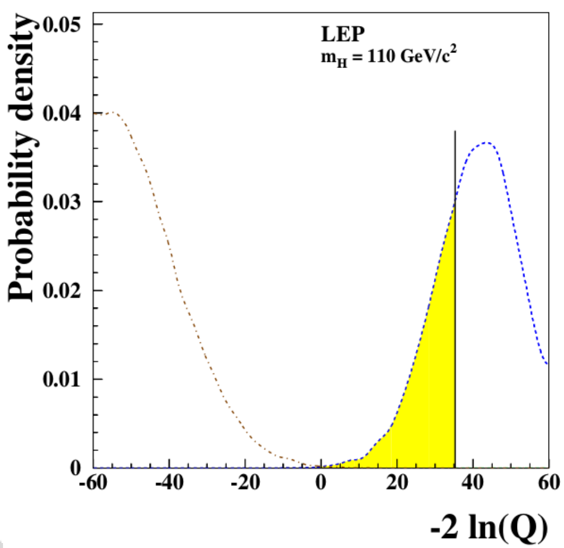
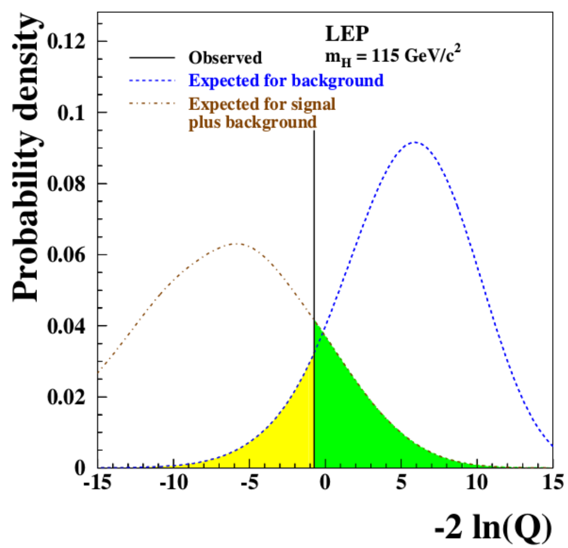






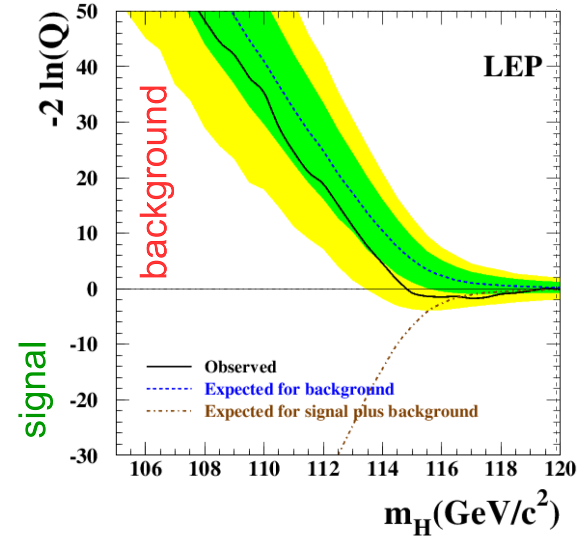
Test Statistic (LEP, remember last lecture)

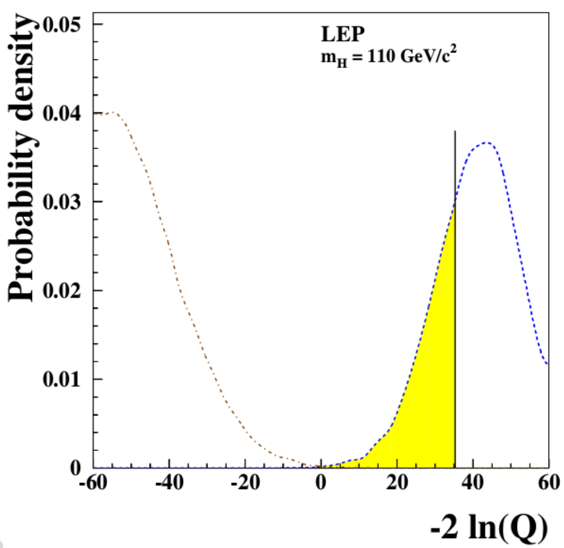
$$\mathcal{L}_{s+b} = \prod_{k=1}^{N} \left(\frac{(s_k+b_k)^{n_k}}{n_k!} e^{-(s_k+b_k)} \cdot \prod_{j=1}^{n_k} \frac{s_k S_k + b_k B_k}{s_k + b_k} \right)$$

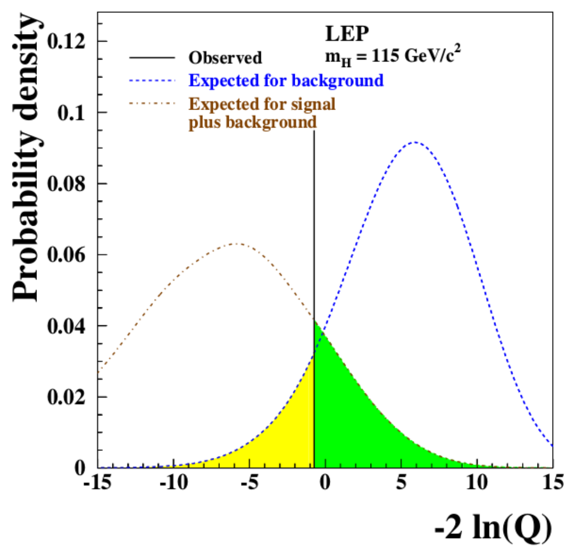
$$\mathcal{L}_{b} = \prod_{k=1}^{N} \left(\frac{b_k^{n_k}}{n_k!} e^{-b_k} \cdot \prod_{j=1}^{n_k} \frac{b_k B_k}{b_k} \right)$$

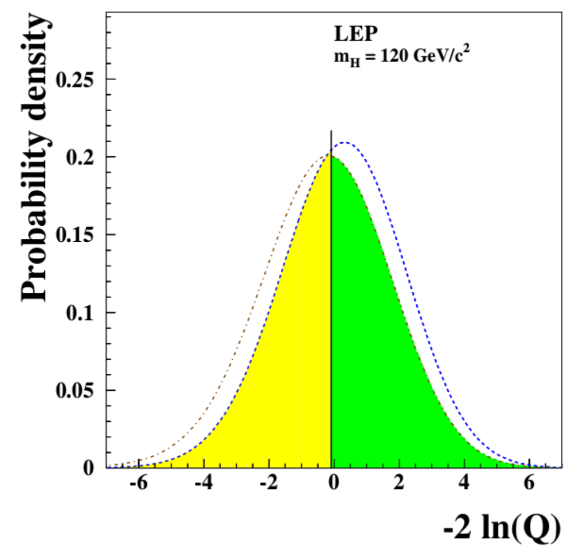
$$Q = \frac{\mathcal{L}_{s+b}}{\mathcal{L}_b} = \prod_{k=1}^{N} \left(e^{-s_k} \cdot \prod_{j=1}^{n_k} \frac{s_k S_k + b_k B_k}{b_k B_k} \right)$$

$$q = -2 \ln Q = 2 \sum_{k=1}^{N} \left(s_k - \sum_{j=1}^{n_k} \ln \left(1 + \frac{s_k S_k}{b_k B_k} \right) \right)$$



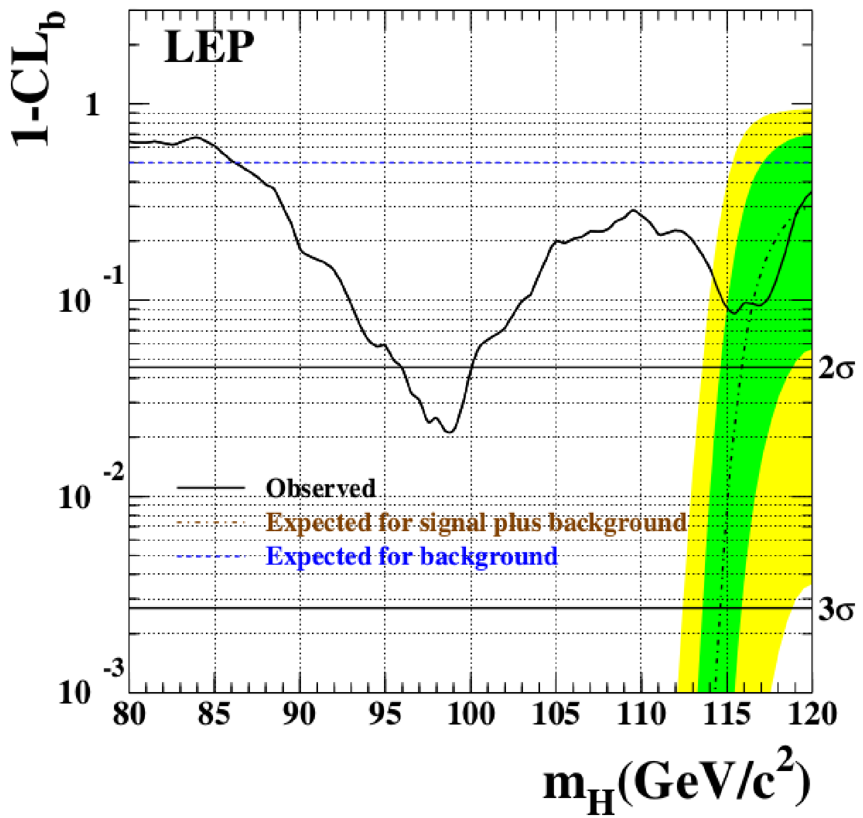




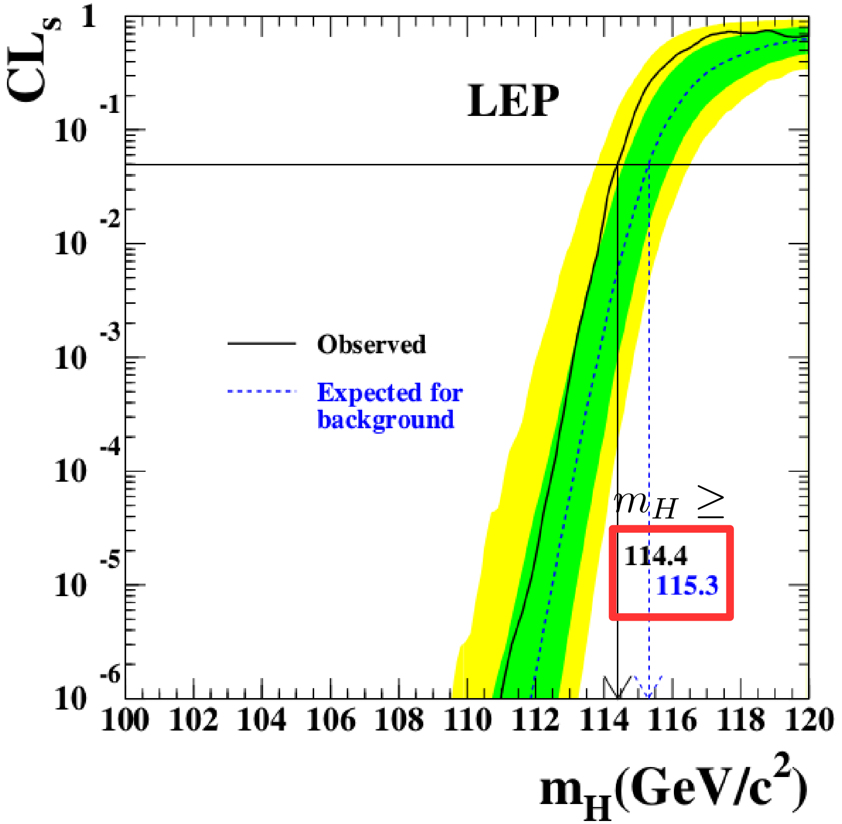


Result (Final Word from LEP)

p-value:



CL_s-limit ($CL_s = \frac{CL_{s+b}}{CL_b}$):



- No signal observed!

Result (Final Word from LEP)

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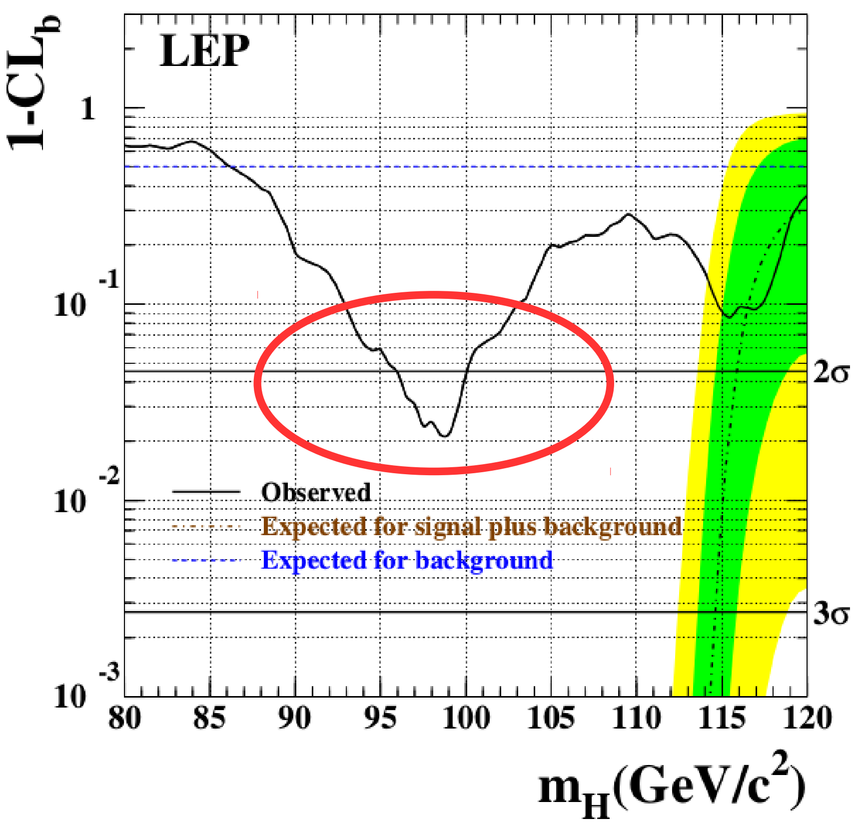

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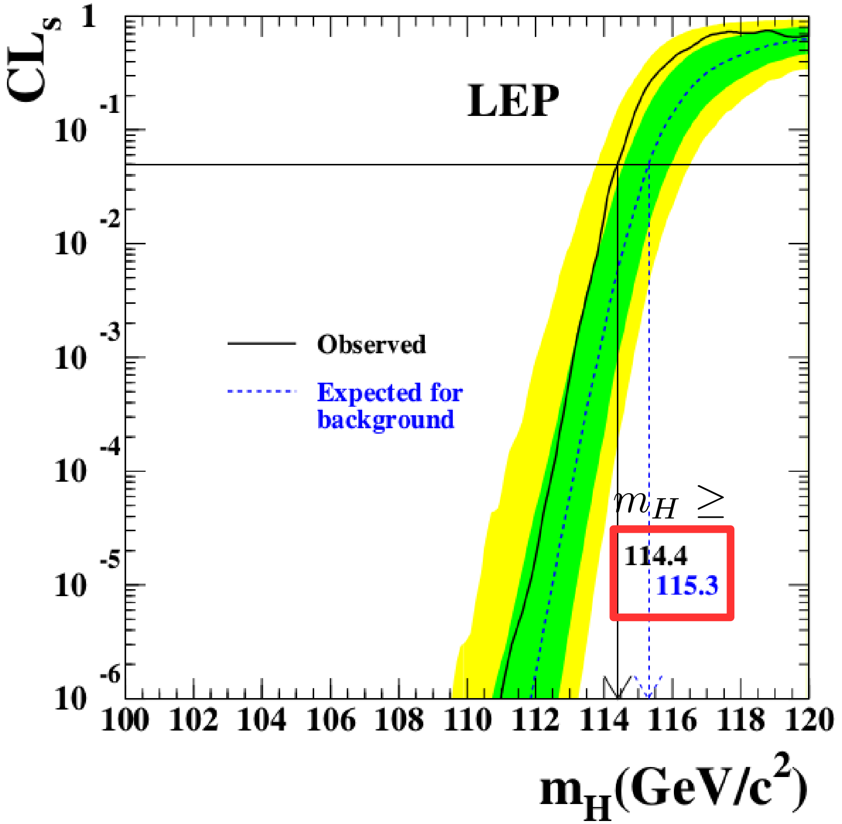

- No signal observed! There is a 2σ effect, but this is not compatible with the SM.

Direct Searches @ Tevatron

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- Also @ Tevatron searches have been conducted at $\sqrt{s} = 1.96\ \mathrm{TeV}$:
- Luminosity: $\mathcal{L}_{\mathrm{int}} \leq 10\ \mathrm{fb}^{-1}$

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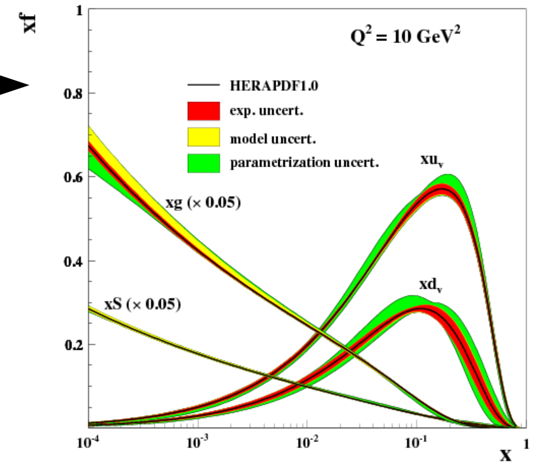
$$x = \frac{125\ \mathrm{GeV}}{1'960'000\ \mathrm{GeV}} \approx 0.06$$



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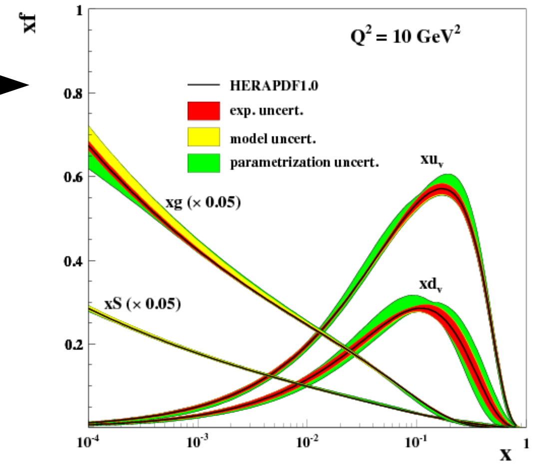
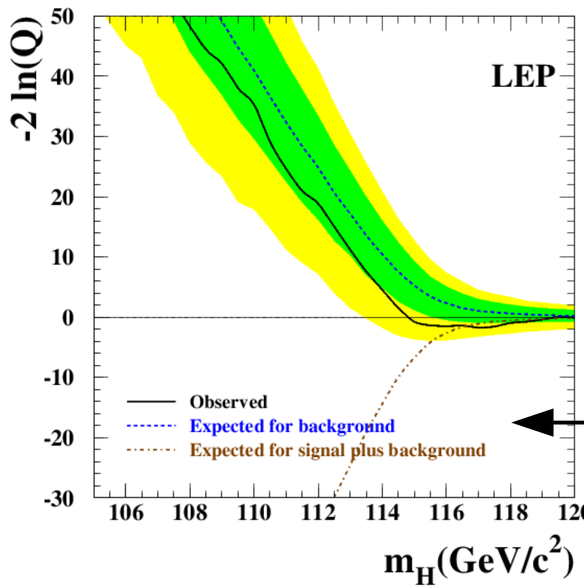
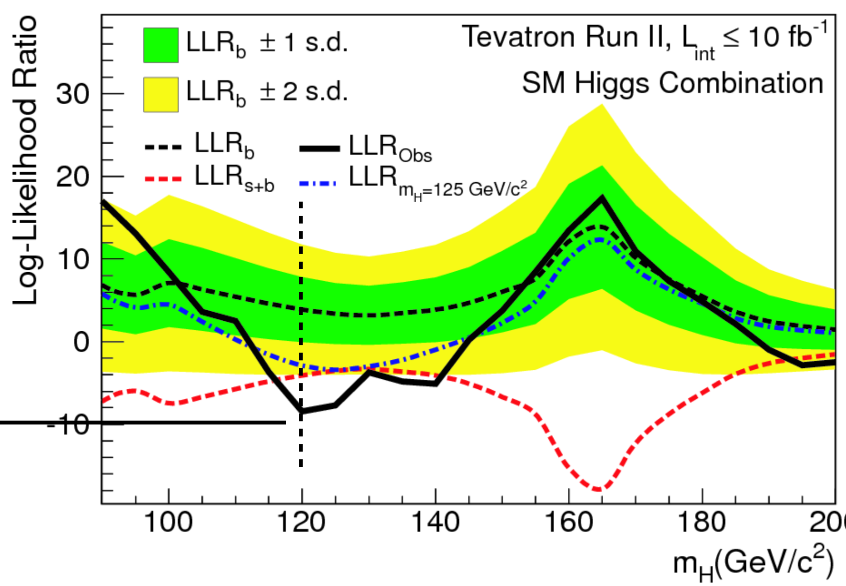


- Luminosity: $\mathcal{L}_{\mathrm{int}} \leq 10\ \mathrm{fb}^{-1}$
- Production/decay modes:

$gg \to H,\ q\bar{q} \to H,\ q\bar{q} \to VH,\ q\bar{q} \to t\bar{t}H$

$H \to bb,\ H \to \tau\tau,\ H \to WW,\ H \to ZZ,\ H \to \gamma\gamma$





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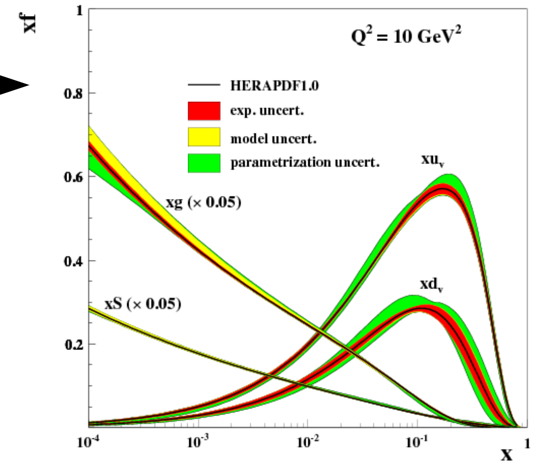

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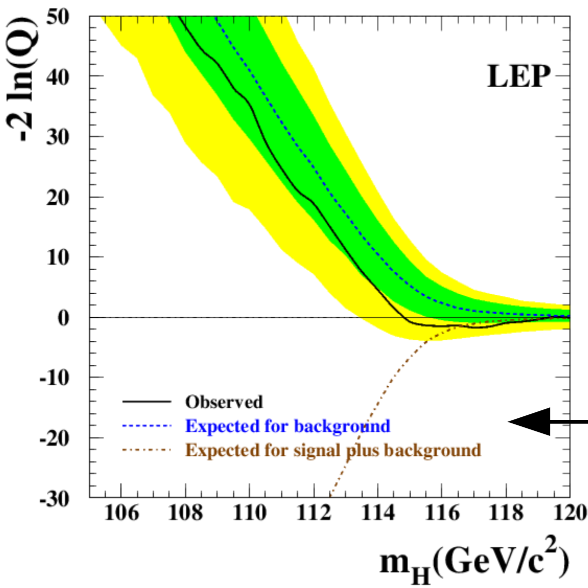
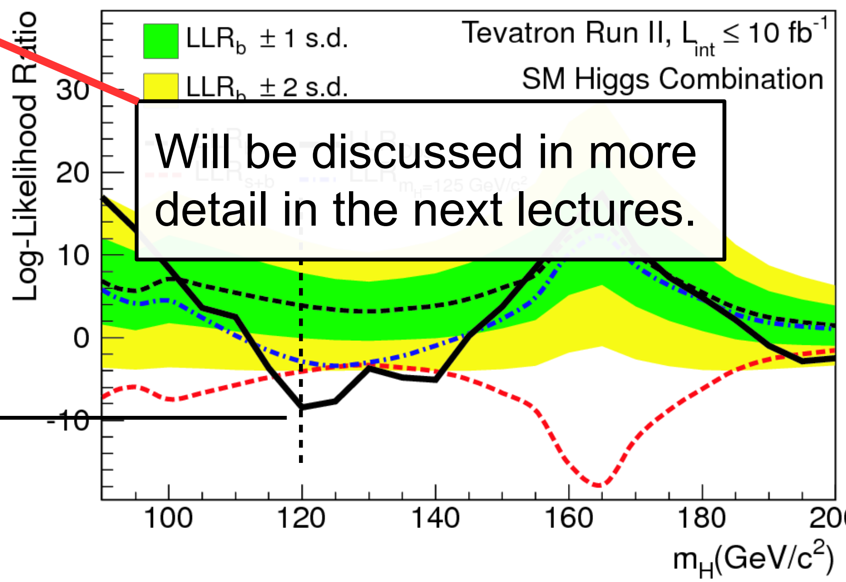
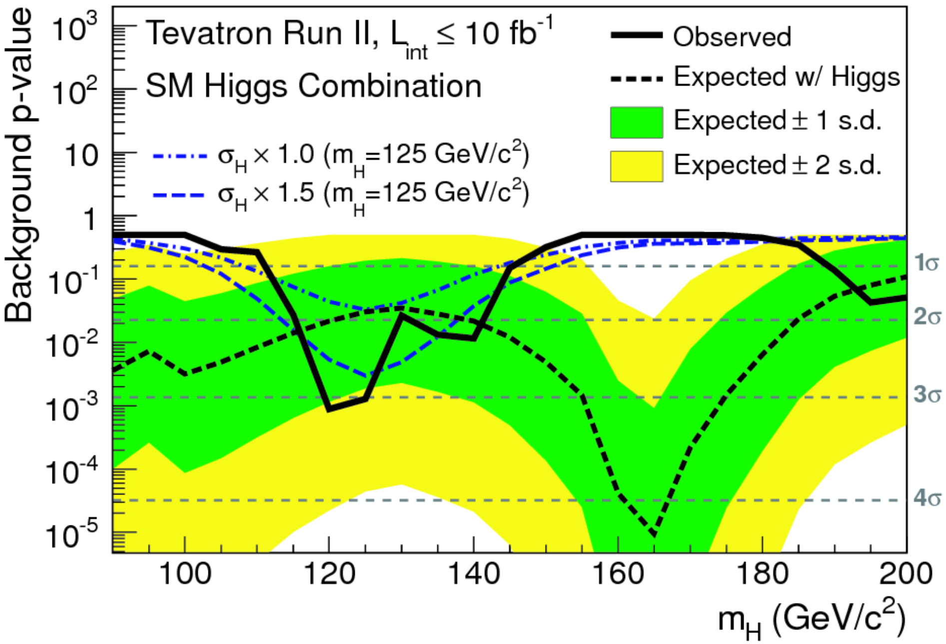




Will be discussed in more detail in the next lectures.

Result (Final Word from Tevatron)

p-value:



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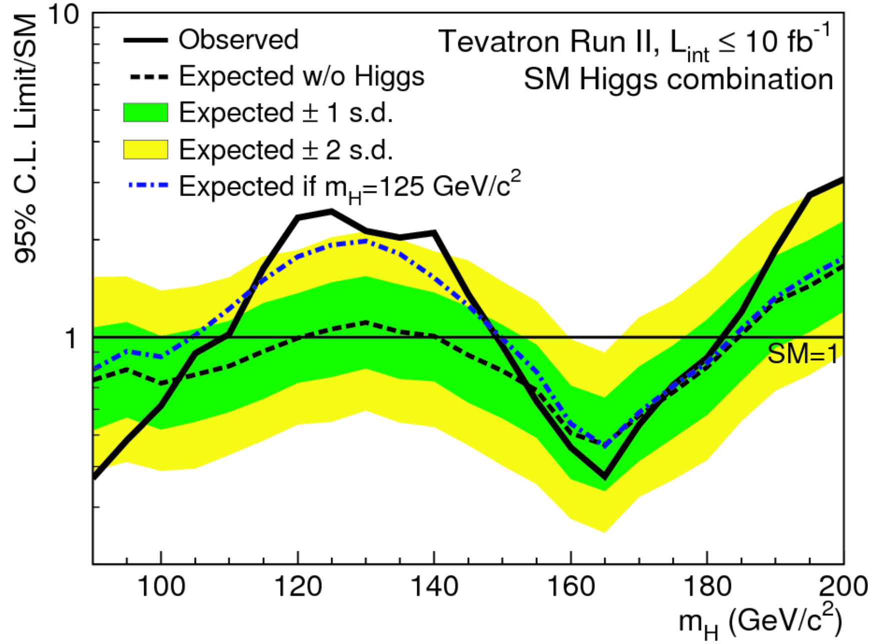

- Sensitivity of Tevatron results driven by $q\bar{q} \to VH,\ H \to b\bar{b}$.
- $\gtrsim 3\sigma$ evidence for a Higgs boson around $m_H \approx 120$ GeV, $\approx 1.5\sigma_{\rm SM}$.

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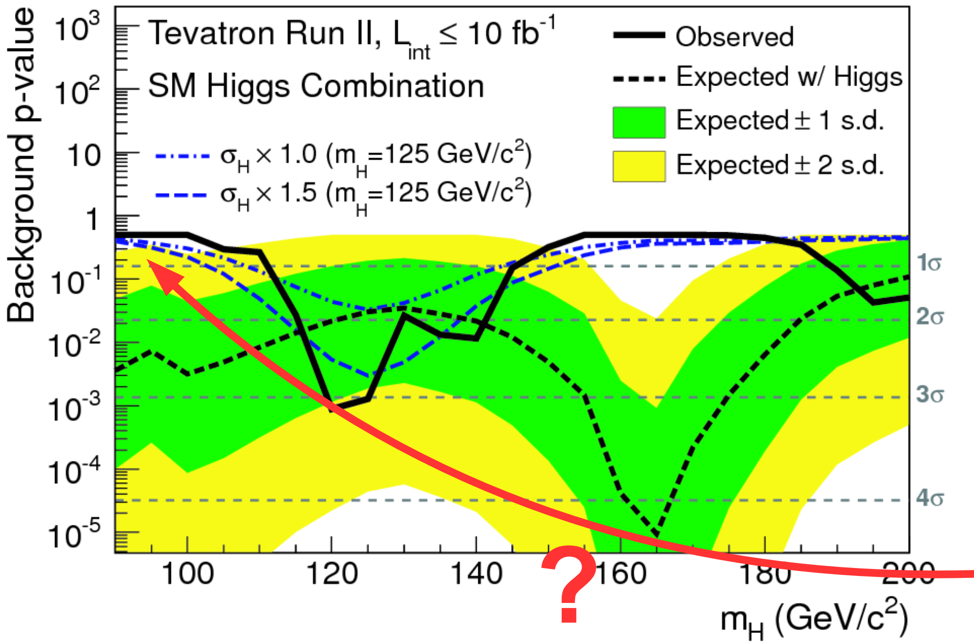

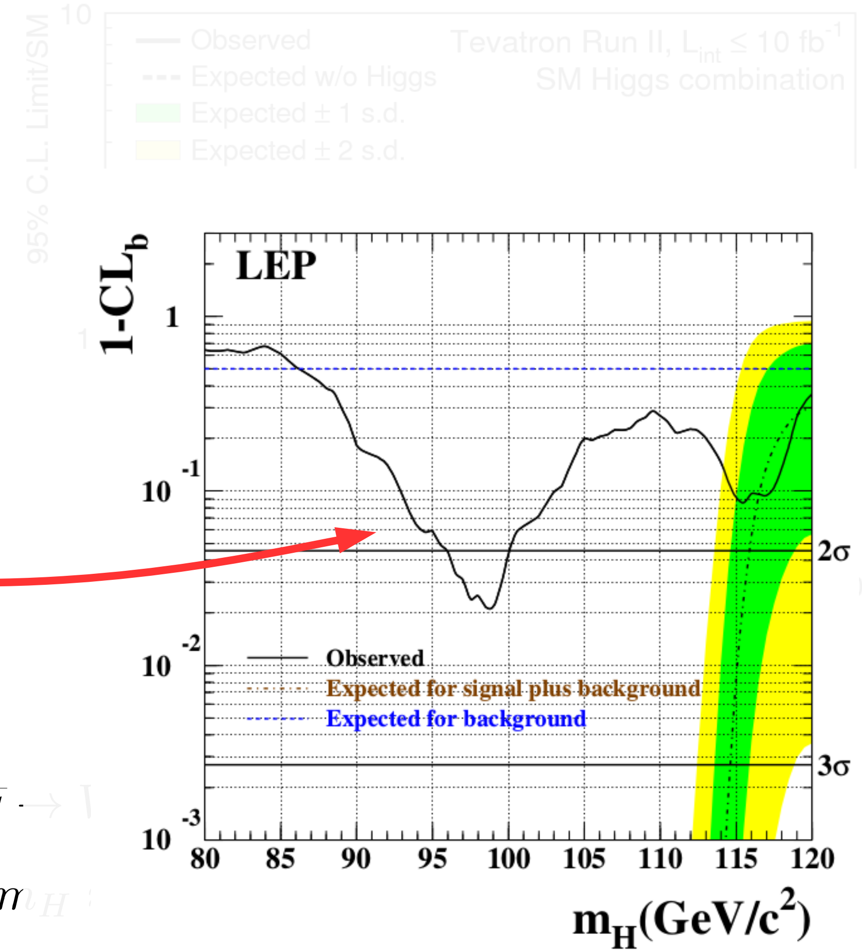

- Sensitivity of Tevatron results driven by $q\bar{q}$ →
- $\gtrsim 3\sigma$ evidence for a Higgs boson around m_H

Concluding Remarks

- The hunt for the Higgs boson had begun in the LEP-II era already.
- We had already good hints where to expect the Higgs (according to the SM) from high precision Z-pole measurements.
- Direct searches @ LEP and @ Tevatron remained inconclusive, since the Higgs boson was out of reach.
- 2010 the dishes were set for the final round...

Sneak Preview for Next Week

- From the next lecture on we will discuss the Higgs discovery at the LHC, the first determination of its properties and perspectives for further surprises in the Higgs sector.
- During the last time slots of the lecture series you will have the chance to study first hand literature on the discovery, with our help.
- Presentations should be in electronic form and of ~20 minutes duration, including discussion. Take it serious. You can discuss your oeuvre with us well in advance of your presentation. Send your slides well in advance to roger.wolf@cern.ch.

Distribution of Seminar Talks

- Precision Electroweak Measurements at the Z Resonance.
- Search for the SM Higgs boson at LEP.
- Search for the SM Higgs boson in the di-photon final sate.
- Search for the SM Higgs boson in the ZZ final state.
- Search for the SM Higgs boson in the WW final state.
- Search for the SM Higgs boson in the di-tau final state.
- Search for the SM Higgs boson in the final state with two b-quarks.
- Search for the SM Higgs boson in the di-muon final state.
- Search for the SM Higgs boson produced in association with top quarks.
- Search for a Higgs boson decaying into invisible particles.

Distribution of Seminar Talks

Karlsruhe Institute of Technology

- Search for neutral MSSM Higgs bosons in the di-tau final state.
- Search for the decay $H \rightarrow hh$, $A \rightarrow Zh$ in multilepton and photon final states.

Seminar Dates: Thursday 03.07. ; Tuesday 08.07. ; Thursday 10.07.

Backup & Homework Solutions